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ELECTRICAL EQUIPMENT FOR TANKS AND MAGNETS

By

C. R. Baldock
E. D. Hudson

Edited by

H. Wesley Savage

April 1947

Clinton Engineer Works -
Tennessee Eastman Corporation
Oak Ridge, Tennessee

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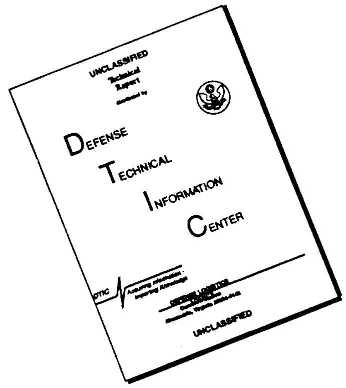

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Russell Baldock
H. Wesley Savage

The Y-12 plant of the Clinton Engineer Works was operated by the Tennessee Eastman Corporation under Contract No. W-7401-eng-23 from January 1943 until May 4, 1947, at which time operations were taken over by Carbide and Carbon Chemicals Corporation for the U. S. Atomic Energy Commission under Contract No. W-7405-eng-26.

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C. R. BALDOCK and E. D. HUDSON

Carbide and Carbon Chemicals Corporation; formerly of Clinton Engineer Works, Tennessee Eastman Corporation

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PROJECT PREFACE

The scope and responsibilities of many of the organizations connected with the electromagnetic process for the separation of uranium isotopes were indicated in the report "Atomic Energy for Military Purposes" by H. D. Smyth. The Clinton Engineer Works—Tennessee Eastman Corporation operated the plant, and it is the purpose of this report to record the developments of the process to its present high efficiency through the efforts of the research, development, engineering, and production groups.

The equipment had been designed against an almost impossible deadline, and fabrication of the equipment and construction of the buildings in which it was to operate were done with speed probably never before known in American industry. Only limited laboratory testing of prototypes of some of the production units was possible, and the design had to be frozen on much of it before any tests could be made. Many of the chemistry problems were still in the laboratory stage when the separation units were being built. Some of the recovery methods used were barely in the pilot-plant stage, and other methods were being explored on a test-tube scale.

One of the more ingenious and characterizing features of the process is the fact that independent separating units are operated in individual vacuum chambers located in a common magnetic field. Many units are fed from the same electric supplies, and from two to sixteen vacuum chambers were joined through common headers to a system of forepumps. It is not surprising, therefore, that problems were encountered which were not previously experienced in the laboratory operation of isolated units.

Many components of the equipment had to be operated for a few days and then taken out of operation so that the processed material could be removed and the unprocessed material recovered and prepared for reuse. Certain components had to be thoroughly cleaned, and many parts had to be replaced and adjusted to critical alignment for reinstallation. The maintenance of a balance in such a cycle of activity, which was also contingent on a steady flow of replacement parts from outside vendors and which at any time might be disrupted

by unexpected failure or difficulty in any part of the process, imposed a supreme test of industrial "know how."

Considerable development and improvement were necessary to bring the production rate of the equipment up to the highest possible level, and all efforts were directed toward this primary objective. As the production rate improved, the corrosion and erosion increased, and this in turn required redesign of many parts.

Part of the experimental work was conducted in pilot plants in the developmental area, but by far the greater portion was done in the production buildings and had to be carried out in such a manner that it did not interfere with production. This imposed a serious limitation on experimentation. The methods of attack were for the most part of a short-range nature, and little opportunity was afforded for research on isolated problems. Speed was paramount.

Men engaged in developmental work joined with representatives from the University of California and worked in groups to hasten the solution of difficult problems. When one problem was overcome they moved to a new one, and the spirit of cooperation was a true expression of their sincere desire to get on with the war effort with the greatest possible speed. As better methods evolved from the laboratory stage, they were incorporated in the production cycle.

Tennessee Eastman is particularly grateful to Dr. E. O. Lawrence and the staff of the Radiation Laboratory of the University of California for their help in this work. Space will permit no more than a statement that we are also grateful to the many other persons and enterprises who made substantial contributions to the success of the work as contractors, suppliers, and consultants.

Russell Baldock
H. Wesley Savage
Coordinating Editors

REPORT PREFACE

It is the purpose of this report to give an account of the electrical engineering phases of the electromagnetic separation process as they relate particularly to the electrical equipment for the tanks and magnets used in operating the calutron for the separation of isotopes.

In general each topic is treated on five points: equipment as received on the job, changes made in the equipment as received to make it operable, service conditions, service record, and experimental and theoretical studies made.

The main subjects covered include the magnet with supply equipment and controls, the high-voltage supplies for tanks used, and the tank auxiliary electrical equipment. The primary power-distribution system was omitted since it is conventional. In the section on the magnet, details of the magnet and its supply along with two types of current regulators used are presented. A discussion of protective gaps is also included. In the section on the electrical equipment for tanks and magnets, the two high-voltage power supplies associated with the three types of calutrons used in the plant and the auxiliary power supplies that were required for operation of the ion sources are discussed.

In the writing of this report the authors were assisted by M. C. Becker, C. F. Holloway, A. N. Kitchen, and A. E. Zobel. F. A. Knox assisted in the editing, and F. T. Howard performed the prepublication technical review.

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PART I

HIGH-VOLTAGE SUPPLIES

INTRODUCTION TO PART I

At Clinton Engineer Works—Tennessee Eastman Corporation, a mass spectrograph was operated in an evacuated tank between the pole faces of a large electromagnet to separate the isotopes of uranium. The mass spectrograph consisted of an ion source, an accelerating-electrode system to draw the ions at uniform velocity into the evacuated space, a liner to define a space of uniform electric-field intensity through which the ions passed, and a receiver to collect the separated isotopic ions. The source was operated at a potential positive with respect to the liner; part of the accelerating-electrode system was operated at a potential negative with respect to the liner; and the liner and receiver both operated at the same potential. Quantity production of these isotopes necessitated high currents to maintain the desired potentials, and the voltage applied necessitated rigid protection measures.

The power supplies and components are divided into three sections, each treated in a separate chapter of this volume, which are as follows:

1. The high-voltage supplies, the primary function of which was to maintain the desired electric fields in the mass spectrograph.
2. Auxiliary supplies, which were associated mainly with the source unit to provide and control vapor and ions.
3. Power and control equipment for activating and maintaining the magnetic fields.

Two high-voltage supplies, called "accell" and "decell" supplies, were used in operating the mass spectrograph. The accell supply provided the voltage between the liner and the most negative electrode of the accelerating-electrode system, and the decell supply provided the voltage between the ion source and the liner. The following two systems were used in the CEW-TEC plant:

1. A "cold" source system, wherein the ion source was operated at ground potential and the accell and decell supplies maintained the other components negative with respect to ground.
2. A "hot" source system, wherein the liner and receiver were operated at ground potential, the decell supply maintained the ion

source positive with respect to ground, and the accell supply maintained the accelerating-electrode system negative with respect to ground.

During operation at the plant there were two types of hot-source mass spectrographs installed and operated. The first of these types was known as the "Alpha II" process; it comprised four ion sources and four sets of collector electrodes operated simultaneously in one mass-spectrograph unit. The second hot-source type was known as the "Beta" or "refining" process. It was smaller than the Alpha II type and had only two ion sources with their respective collector electrodes operated as a unit. The one cold-source type of mass spectrograph, known as the "Alpha I" process, comprised two ion sources and associated collectors operated simultaneously in one unit. The Alpha I process differed from the others in that the ion sources were operated at ground potential.

In general, the operation and requirements of these three types of mass spectrograph were similar. Differences in the detailed arrangement of the component power supplies arose depending on the particular unit under discussion, i.e., a hot- or cold-source unit, and on the number of ion sources that were operated as a unit.

[Note: In all three processes, Alpha I, Alpha II, and Beta, the accell supply was also known as the "G" supply. Where the decell supply was used to maintain the liner at a negative potential, in the cold-source system of Alpha I, it was commonly known as the "C" supply. In the hot-source systems of both Alpha II and Beta, where the liner was at ground and the decell supply maintained the ion source at a positive potential, the decell supply was known as the "M" supply.]

Chapter 1

GENERAL DESCRIPTION OF HIGH-VOLTAGE SUPPLIES

To aid in describing the high-voltage supplies, an over-all picture of the three systems used and the interconnection between the accell and decell supplies is presented in the form of three block diagrams. The first, Fig. 1.1, is for the cold-source system of the Alpha I process; the second, Fig. 1.2, is for the hot-source system of the Alpha II process; and the third, Fig. 1.3, is for the hot-source system of the Beta process.

It will be noted from these diagrams that the power-distribution systems were essentially alike, power for the rectifiers being derived in each case from a 60-cycle 3-phase 1,000-kva 13.8-kv to 460-volt unit-type substation having a transformer with automatic tap changers to hold the voltage within 1.3 per cent of the desired value. The unit-substation transformer was protected by a 1,600-amp air circuit breaker, which fed a group of 450-amp air circuit breakers. Each of these 450-amp air circuit breakers, in turn, fed one or more combinations of accell and decell rectifiers, depending on the load of these individual rectifiers. In the case of Alpha I, four of these rectifier combinations were fed from each 450-amp air circuit breaker. Beta had two rectifier combinations per circuit breaker, and Alpha II, with its higher load, had only one rectifier combination per circuit breaker.

Each rectifier bus was fed through a manually operated 460-volt disconnect, which supplied power for the rectifiers and for the control circuits. The main rectifier bus was energized by a main power contactor and, except in Alpha II, was protected by overload relays (type PAC). The accell and decell rectifiers derived their power from the main power bus through a combination of two contactors and associated resistors so connected that the resistors, after limiting the inrush current to the rectifier, were removed from the rectifier power-supply circuit. This combination of resistors and contactors

was known as a "step-start" circuit. In Alpha I and Beta, individual step-start circuits were supplied for each rectifier, and in Alpha II both rectifiers were supplied through a common step-start combination.

The primary circuit of each accell and decell rectifier included an induction voltage regulator and a time-delay overload relay (type IAC) equipped with instantaneous attachment.

The accell and decell rectifiers of the three types were high-voltage low-current thermionic-vacuum-tube multiple-phase rectifiers. Since the output ripple from each of these rectifiers was higher than permissible for satisfactory operation, each rectifier was supplied with a capacitor filter, this filter being equipped with a charge current-limiting resistor and a discharge current-limiting resistor.

Each accell rectifier had the degree of regulation normal for this type of equipment. Manual voltage adjustment was provided by the induction voltage regulator. In Alpha II and Beta equipment, current-limiting protection for this rectifier was provided by means of a thermionic high-vacuum diode tube which was operated under temperature-emission-limited conditions in order to limit the short-circuit current that the rectifier would be required to provide. Such protection was not provided in Alpha I equipment.

Since the load to the accell rectifier was highly variable owing to sparking that occurred in the mass spectrograph, transients having a steep wave front were encountered. The rectifier was protected from these transients by means of a resistor-capacitor line-terminating network.

Although a rectifier with filter provided adequate regulation for the accell supply, the requirements for the decell power supply were more rigid. The absolute value of the decell voltage determined the velocity of the ions and the position at which the ion beam would be focused in the mass spectrograph, but the absolute magnitude of the accell voltage determined only the number of ions that would be withdrawn from the ion-source plasma. This requirement for a closely regulated decell voltage necessitated the use of a regulator in the output of the decell rectifier. The regulator used was a series type consisting of a high-vacuum triode tube, associate voltage amplifier, and voltage sampler connected to the output of the power supply. In Alpha I the regulator tube was placed in the ground side of the decell rectifier, and in Alpha II and Beta the regulator tubes were placed in the ungrounded circuit. This regulator system will be described in detail in Chap. 7.

In the Alpha I equipment a high-vacuum diode tube was placed in the ungrounded circuit from the decell rectifier. This tube was oper-

ated temperature-emission-limited in the same way as the limiter tube to be described in the accell rectifier. The tube was used as a means of limiting the maximum short-circuit current from the decell rectifier during periods of sparking in the mass spectrograph. In Alpha II and Beta equipment the regulator tube was operated temperature-emission-limited to limit the short-circuit current required from the rectifier. The high-voltage regulators supplied for the Alpha I and Alpha II equipment were automatically controlled to a further degree by a beam regulator that was designed to prevent contamination of the isotopes collected in the receiver pockets. The operation of this regulator will be described in detail in Chap. 7. The output circuit of the regulated decell rectifier was protected from steep wave-front transients by a condenser-resistor network similar to that described for the accell rectifier circuit.

Besides the equipment described above there have been included in the three block diagrams the necessary power circuits that feed the filaments of the rectifier, regulator, and limiter tubes. These filaments were fed through a combination of contactors, induction voltage regulators, and suitable filament transformers in such a manner that it was possible to adjust the individual filament voltages to the most desirable operating value. Induction voltage regulators in these filament circuits served a further use in that the control circuit was so arranged that before power was applied to any filament circuit the induction voltage regulator automatically went to the minimum-voltage position to prevent a high inrush current to the tube filament.

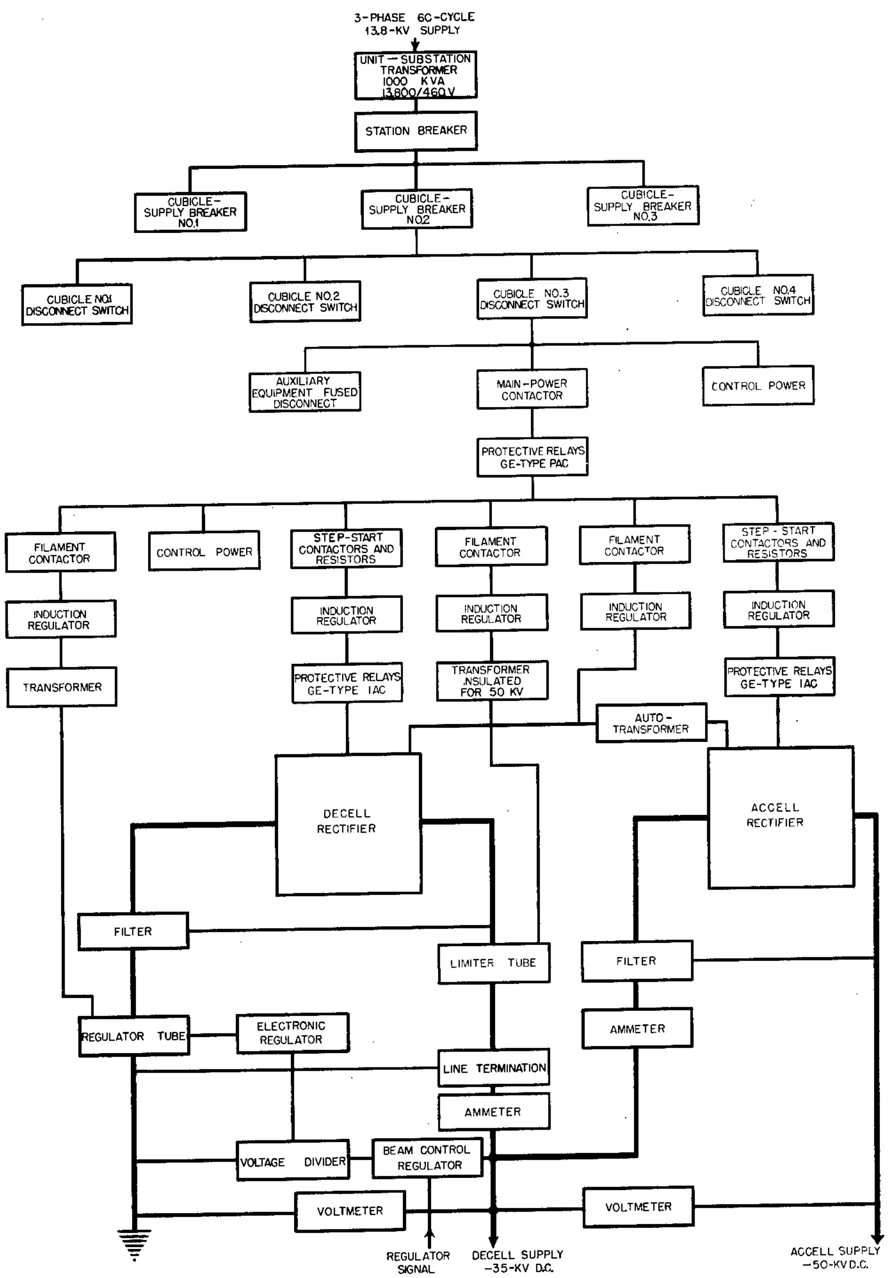


Fig. 1.1 —Block diagram of Alpha I high-voltage supply.

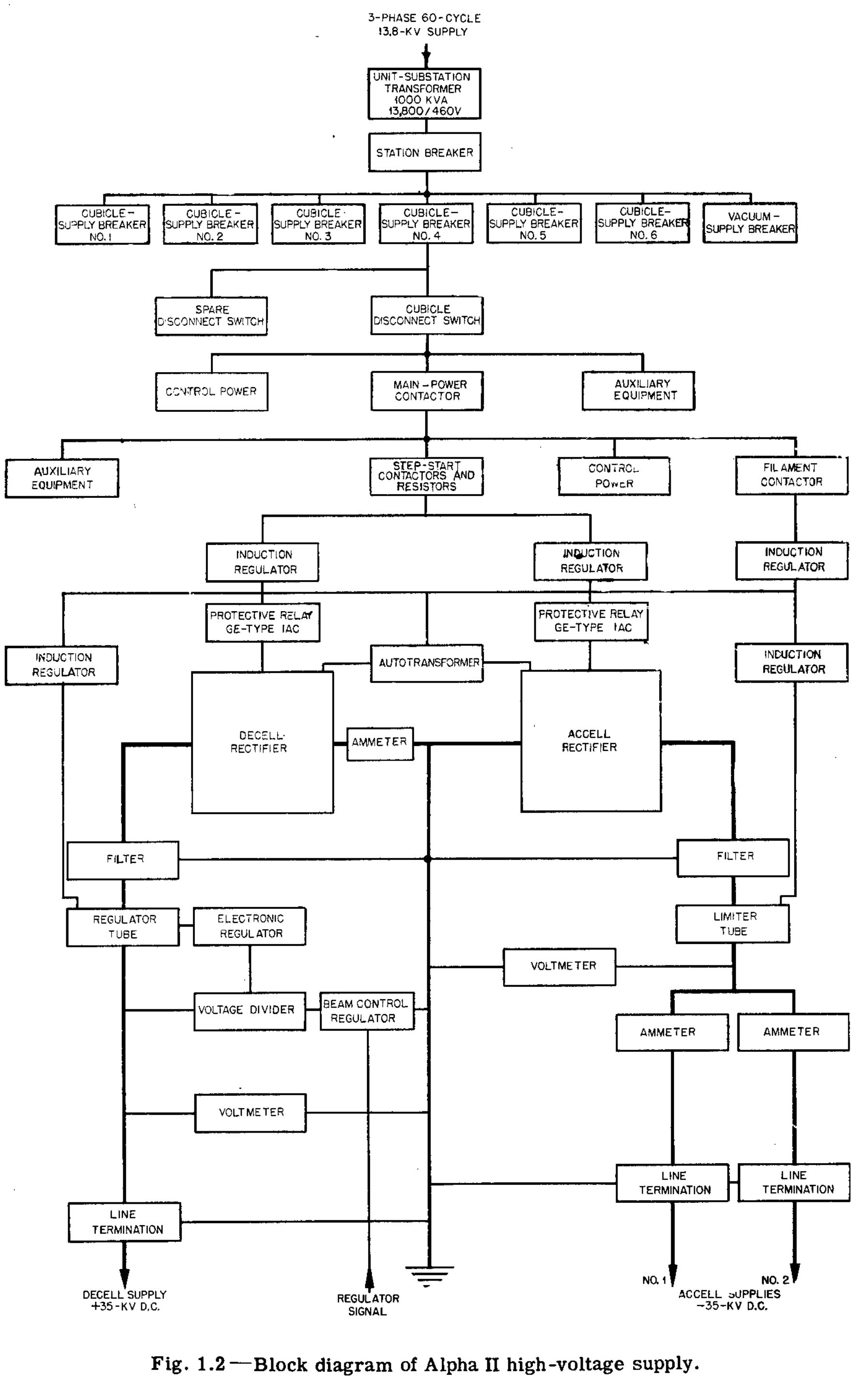


Fig. 1.2—Block diagram of Alpha II high-voltage supply.

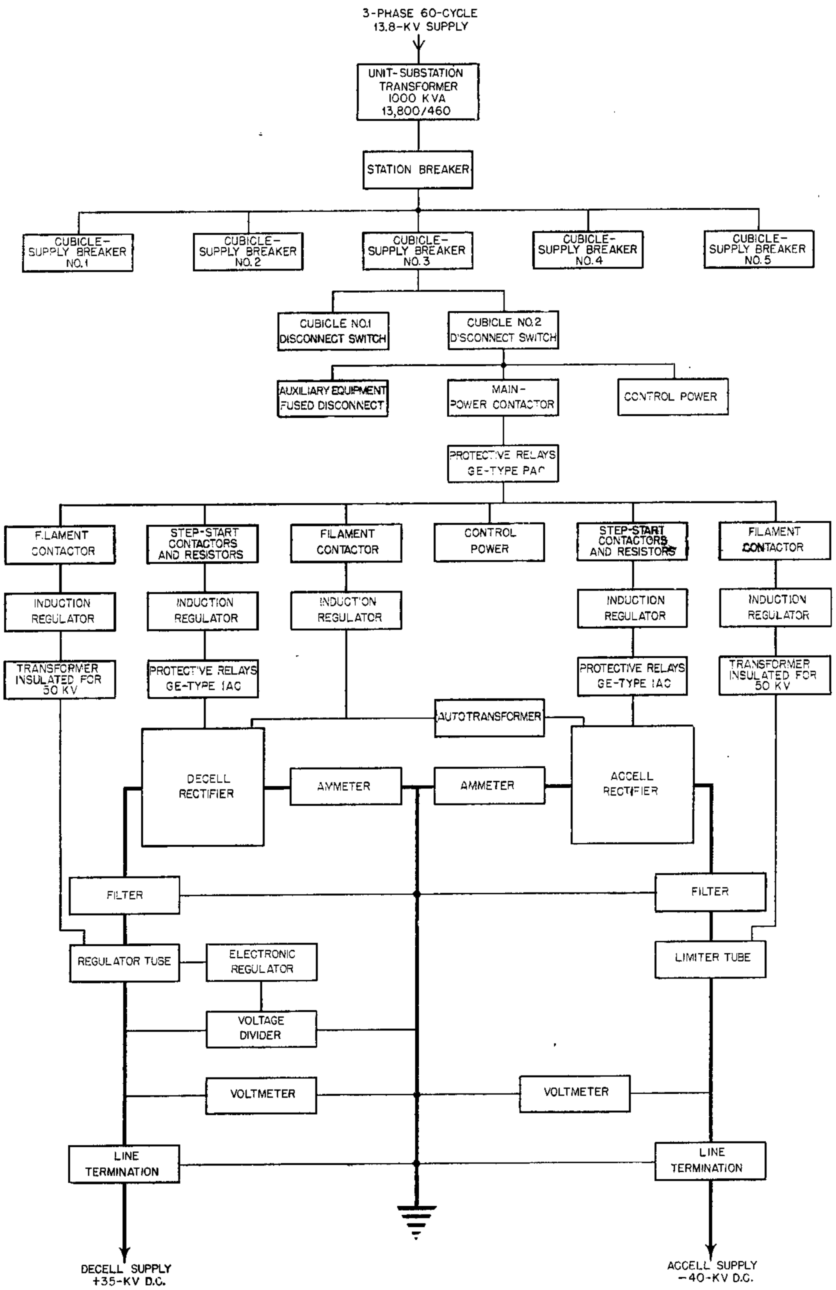


Fig. 1.3—Block diagram of Beta high-voltage supply.

Chapter 2

PHYSICAL DESCRIPTIONS AND RATINGS OF HIGH-VOLTAGE SUPPLIES

The equipment installed at CEW-TEC was patterned on a unit "channel" system. A channel consisted of the necessary high-voltage supplies, associated low-voltage supplies, and all control equipment necessary for the operation of one mass-spectrograph unit. A major portion of this equipment was housed in a steel-clad cubicle known as the "high-voltage" cubicle.

The Alpha I cubicle was approximately 4 by 12 by 10 ft high, weighed 6 tons, and housed the two high-voltage rectifier supplies, together with the necessary control equipment for these supplies and for the low-voltage supplies to be described in Part II. Figures 2.1 and 2.2 are external views of one of these cubicles, and Figs. 2.3 to 2.5 show the internal construction. The Alpha II high-voltage cubicle was approximately 8 by 14 by 12 ft high, had a gross weight of 14 tons, and housed the two high-voltage rectifier supplies with their control circuits and the controls for the various low-voltage supplies. Some of the low-voltage equipment was also located in the same cubicle. Figure 2.6 is an external view of this cubicle, and Figs. 2.7 and 2.8 show the construction of the cubicle. The Beta high-voltage cubicle was approximately 5 by 15 by 10 ft high, weighed approximately 10¾ tons, and housed the high-voltage supplies, low-voltage-supply controls, and one of the low-voltage supplies. Figure 2.9 is the external view of the Beta high-voltage cubicle, and Figs. 2.10 and 2.11 show some of the construction details.

Forced-air ventilation was provided for these cubicles by a centrifugal blower, which drew air in at the bottom of the cubicle from a filtered-air chamber and exhausted it through an outlet at the top of the cubicle into an exhaust chamber. All controls were mounted on the front face of the cubicles. Doors were located at both the front and rear for access by maintenance personnel.

1. ACCELL RECTIFIER: DESCRIPTION AND RATING

Owing to the differences in load requirements for the three different systems the individual rectifier ratings were (1) Alpha I, d-c output rated 15,000 volts, 0.4 amp; (2) Alpha II, d-c output rated 35,000 volts, 1.0 amp; and (3) Beta, d-c output rated 40,000 volts, 0.4 amp. The Alpha I and Beta rectifiers were connected 3-phase delta to zigzag Y. The Alpha II rectifier was double 3 phase with interphase transformer.

The Alpha I rectifier transformer was rated at 60 cycles, 3 phase, 10 kva, 775/26,500 volts line to neutral. The Alpha II transformer had a name-plate rating of 60 cycles, 3 phase, 50 kva, 805/40,600 volts, with an interphase transformer rated at 180 cycles, 11.5 kva, 23,000/11,500 volts. The Beta rectifier transformer was rated at 60 cycles, 3 phase, 26.3 kva, 575/44,200 volts line to neutral.

The primaries of these transformers were excited by induction voltage regulators having the following ratings: Alpha I, 3 phase, 60 cycles, 5.6 kva, 460 ± 380 volts, 8.5 amp; Alpha II, 3 phase, 60 cycles, 24 kva, 460 ± 380 volts, 36.5 amp; and Beta, 3 phase, 12.2 kva, 460 ± 380 volts, 18.5 amp. These induction voltage regulators were, in turn, fed from the main 460-volt power bus in the high-voltage cubicle. Each of the regulators was supplied with forced-air cooling.

In order to limit the inrush current to the rectifier a step-start circuit was used, which consisted of a contactor feeding from the main 460-volt power bus through three resistors into the rectifier-supply induction voltage regulator. As soon as this contactor had closed, auxiliary contacts energized a second contactor which tied the induction voltage regulator directly to the power bus, shunting out the first contactor and the series resistors. Thus lower than normal voltage was supplied momentarily to the induction voltage regulator while the heavy inrush magnetizing current was flowing. The voltage to the induction voltage regulator was then raised to the normal 460 volts by the operation of the second contactor.

In Alpha I equipment the step-start circuit consisted of a 25-amp 3-phase contactor and three 8-ohm 80-watt resistors. This combination was shunted by a second 25-amp 3-phase contactor. The Alpha II equipment used a 150-amp contactor and two 1.5-ohm 180-watt resistors connected in parallel in each phase. This combination was shunted by a main contactor rated at 300 amp. This step-start circuit for Alpha II was common for both the accell and decell rectifiers. The Beta equipment was supplied with a contactor rated at 25 amp, operating with 4-ohm 120-watt resistors, and a shunting contactor rated at 75 amp.

An individual insulating transformer was required for each tube in the rectifier circuit because the tube-filament return was connected to its respective phase of the power transformer. For Alpha I and Beta three filament insulating transformers were required. These individual transformers were single phase with their primary windings connected in delta across the secondary of the filament autotransformer. The transformers had individual ratings as follows: single phase, 60 cycles, 0.551 kva, 805/22.5 volts. The filament transformers for Alpha II carried the same rating, but the double-Y rectifier required the use of six insulating transformers instead of three as used in the other two rectifiers.

The assembly of the rectifier transformers was unique in that the main power transformer and the necessary filament insulating transformers were housed in one oil-filled transformer case. The secondaries of the filament insulating transformers were directly connected inside the case to the respective phases of the main power transformer, and the filament leads were brought out in bushings through the case cover. Tube sockets were mounted on the outer ends of these high-voltage bushings, and the rectifier tubes extended vertically above the sockets. A common anode bus for the tubes was mounted and insulated from the transformer-case cover. This arrangement produced a unit type of rectifier supply. Schematic diagrams of the accell rectifiers are shown in Figs. 2.12 (Alpha I and Beta) and 2.13 (Alpha II).

As originally installed all accell rectifiers were equipped with radiation-cooled General Electric KC4 diode tubes. This tube had a thoriated-tungsten single-phase self-supporting directly heated spiral filament, rated at 20 volts, 24.5 amp. The maximum peak plate current was 0.75 amp. The tube had a peak inverse voltage rating of 150,000 volts with an average plate dissipation of 750 watts. Characteristic curves of this tube are given in Fig. 2.14.

The tube, a glass-enclosed diode with an over-all length of approximately 25 in. and a 6-in. maximum diameter, was designed for convection air cooling. Figures 2.15 to 2.20 are views of the accell rectifier showing the rectifier tubes mounted in position. These views also show the physical construction and the mounting of the main power transformer, interphase transformer, and filament insulating transformer.

The d-c output voltage of each of the accell rectifiers was filtered by a capacitor filter. Excessive charge and discharge currents to the filter were limited by a charge and discharge resistor. The Alpha I filter consisted of one 0.05-μf 25-kv d-c capacitor and one charge-current-limiting resistor of 200 ohms, 50 watts, plus two discharge-current-limiting resistors connected in series and rated 400 ohms,

160 watts, and 640 ohms, 160 watts, respectively. The Alpha II filter had a 0.2 μf 50-kv d-c capacitor with charge and discharge resistors each rated 100 ohms, 458 watts. The Beta filter capacitor was rated 0.25 μf, 50 kv, direct current and was built up of two sections (each 0.5 μf, 25 kv) connected in series and mounted in a common case. An external voltage divider consisting of two series-connected 50-megohm resistors was connected across this capacitor with the center tap of the divider connected to the center tap of the capacitor and its case. The charging resistor for this condenser combination was rated 200 ohms, 50 watts. The discharge resistor, which was a series-parallel combination, was rated 400 ohms, 200 watts. Since multiple-phase rectifiers were used in all three plant applications, this filtering was adequate to hold the ripple voltage to less than 2 per cent of the d-c output voltage.

The accell rectifiers were protected on the primary side from overload by induction-disk time-delay overcurrent relays. Protection from rectifier-tube-gas kicks and phase-to-phase and bushing flashovers in the rectifier was provided by the plunger-type instantaneous attachment provided with these relays. These relays were controlled by current transformers located in the main transformer supply line, with ratios as follows: Alpha I, 2 to 1; Alpha II, 6 to 1; and Beta, 3½ to 1.

Metering on the output circuit of the accell rectifiers was provided by a d-c milliammeter and d-c voltmeter, which read the actual voltages and currents supplied to the mass spectrograph. In Beta the meters were protected from transient voltages reflected back on the high-voltage line. A feature of this metering was the capacitor, choke, Thyrite, and film-gap network. In the Alpha II equipment two individual circuits from the accell rectifier were required, each having a d-c milliammeter. The meters were mounted on individual panels and insulated from ground to withstand the accelerating voltage. The output voltmeter was mounted at ground potential, and both the milliammeter and voltmeter were protected from surges as described above. In the Alpha I equipment the accell supply was connected in cascade with the decell supply and was at all times operated at a negative potential equal to the decell voltage. Both the d-c milliammeter and d-c voltmeter were insulated from ground to withstand the decell voltage. These meters were also suitably protected from surges as has previously been described. The meters in all cases had a full-scale value equal to one and one-half times the maximum rated output of the rectifier.

2. DECELL RECTIFIER: DESCRIPTION AND RATING

As in the case of the accell rectifier, the decell rectifier also varied in the nominal output rating depending on the class of service and the anticipated load requirements of the individual mass spectrographs. The nominal d-c ratings of the three decell rectifiers were as follows: Alpha I, 35,000 volts, 1.0 amp; Alpha II, 35,000 volts, 2.0 amp; and Beta, 35,000 volts, 1.0 amp. In all cases the name-plate rating of the regulated supply has been given rather than the rating of the rectifier in order to indicate the actual output value after losses in the electronic regulator have been subtracted from the rectifier output.

The main power transformers for the Alpha I and Beta rectifiers had identical ratings as follows: 3-phase delta to double Y with interphase transformer, 60 cycles, 51.5 kva, 575/42,000 volts line to neutral. The interphase transformer was rated 180 cycles, 11.5 kva, 23,100/11,550 volts. Although the power ratings of the transformers in the two applications were identical, they differed in physical construction because the Alpha I transformers operated with the neutral at approximately ground potential and with a negative high-voltage output, but the Beta rectifier operated with a positive output voltage at the neutral, which required the neutral bushing to stand the full rectifier potential. The Alpha II rectifier was a 3-phase full-wave type. The power transformer was connected delta-Y and was rated 117 kva, 60 cycles, 620/41,400 volts line to line.

The primaries of these transformers were excited by induction voltage regulators having the following ratings: Alpha I, 3 phase, 60 cycles, 10.3 kva, 460 ± 115 volts, 51.7 amp; Alpha II, 3 phase, 60 cycles, 30.2 kva, 460 ± 160 volts, 109 amp; and Beta, 3 phase, 60 cycles, 10.3 kva, 460 ± 115 volts, 51.7 amp. These induction voltage regulators were fed from the main 460-volt power bus in the high-voltage cubicle and were supplied with forced-air cooling. As in the accell rectifier, the decell rectifier was also equipped with a step-start circuit between the power bus and the induction voltage regulator. In Alpha I this consisted of a 50-amp contactor and 2-ohm 80-watt resistors, the combination being shunted by a 75-amp contactor. In the description of the Alpha II accell rectifier given in Sec. 1, it was explained that both the accell and decell rectifiers used a common step-start circuit, and the component parts of this circuit were given. These are being repeated here for ready comparison of the three types of decell rectifier circuits. The ratings of the component parts of Alpha II were, for the first contactor, 150 amp with two 1.5-ohm 180-watt resistors in parallel, and for the second contactor, 300 amp. The step-start

circuit for the Beta equipment used a 50-amp first contactor, in conjunction with 2-ohm 120-watt resistors, and a 75-amp second contactor.

The physical construction of the decell rectifiers was similar to that used for the accell rectifier. The main transformer, interphase transformer, and filament transformers were all mounted in a common oil-filled steel tank. In Alpha I and Beta the filament transformers were internally connected to the respective phases of the main power transformer, and filament leads were brought out through high-voltage bushings mounted in the cover of the transformer case. The tube sockets for the air-cooled diode rectifiers were mounted on the external ends of these bushings, and the rectifier tubes extended vertically from the sockets to a common anode bus. The major difference between the Alpha I rectifier assembly and the Beta assembly was that the differences of operating polarity required the neutral of the Beta transformer to be brought out through a high-voltage bushing capable of withstanding the maximum rectifier potential.

The Alpha II rectifier assembly had, in general, the same design features as the two previously described. However, since this rectifier was a 3-phase full-wave type using water-cooled diode rectifier tubes, the filament leads for these tubes were brought through five high-voltage bushings mounted in the top cover of the rectifier case. Three Lapp coils in conjunction with three standoff insulators mounted on the same cover were used to support the necessary water jackets. Only three Lapp coils were needed in the water line because three of the rectifier tubes operated with their anodes at ground potential. However, it will be noted (Figs. 2.15 to 2.20) that, although these tubes were operated with anodes at ground potential, the water jackets were actually mounted on standoff insulators. This was done simply to maintain a uniform height for all six tubes.

Owing to the fact that in Alpha I and Beta the main power transformers had individual phase leads connected directly to the cathode of the rectifier tubes inside the transformer, it was necessary to have filament insulating transformers for each individual tube in these rectifiers. The Alpha I and Beta rectifiers were equipped with the same type of rectifier tube, and the individual filament insulating transformers were rated single phase, 60 cycles, 1.551 kva, 805/22.5 volts. The primaries of these transformers were connected delta. The Alpha II rectifier had a single filament insulating transformer, the primary being delta connected and having six individual secondaries connected to the tube filaments. The main power-transformer phase leads were connected to the rectifier cathode returns inside the

transformer case. This transformer was rated 3 phase, 60 cycles, 7.17 kva, 804/23 volts. Schematic diagrams of these three-rectifiers are shown in Figs. 2.13 (Alpha I and Beta) and 2.21 (Alpha II).

The original rectifier tubes installed in the Alpha I and Beta decell rectifiers were General Electric KC-4 radiation-cooled diode tubes. These are described and their electrical and physical characteristics are given in Chap. 4, Sec. 2.

Owing to the higher output current and the difference in the rectifier circuit connection of the Alpha II decell rectifier, a tube with a higher average anode current was required. The tube supplied with this equipment was the General Electric GL-605. It was a water-cooled diode with a single-phase tungsten double-V filament rated at 22 volts, 52 amp. It had a maximum peak plate current rating of 7.5 amp and an average plate current of 2.0 amp. The peak inverse voltage rating was 50 kv, and the average plate dissipation was 20 kw. Characteristic curves of this tube are given in Fig. 2.22. The tube had a water-cooled copper anode ⅛ in. thick and 3³⁄₁₆ in. in diameter requiring a cooling water flow of 15 gal per minute. The maximum diameter of the glass envelope at the filament end was 5⅛ in., and the over-all length was 24½ in. Figures 2.23 to 2.29 are views of the three types of decell rectifiers showing the rectifier tubes mounted in position. These views also show the physical construction and mounting of the main power transformer, interplate transformer, and filament insulating transformers.

The d-c output voltage of the decell rectifiers was filtered by a capacitor filter. The charge current and the discharge current from this filter were limited by means of charge and discharge resistors. The Alpha I filter consisted of three 0.025-μf 50-kv capacitors connected in parallel with charge and discharge resistors, each rated 200 ohms, 200 watts. The Alpha II rectifier was filtered by three 0.2-μf 50-kv capacitors connected in parallel. The charging current of the capacitors was limited by three 71-ohm 468-watt resistors connected in series. Three similar resistors were used for limiting the discharge current from this capacitor. The output filter for the Beta rectifier consisted of a 1.0-μf 50-kv capacitor. The capacitor was made up of four double sections in parallel, a 50-megohm resistor being connected across each section to form a voltage divider. The center tap of the divider was connected to the center of the capacitor section and to the case. The charging resistor for this capacitor was a 200-ohm 200-watt unit. A similar discharge-current-limiting resistor was provided. The filter was adequate to hold the ripple voltage at the output of each of these rectifiers to less than 1 per cent of the d-c output value.

Overload protection for the decell rectifier was provided by means of overcurrent induction-disk time-delay relays located in the primary power circuit to these rectifiers. Protection from tube-gas kicks and phase-to-phase and bushing flashovers in the rectifier was provided by the plunger-type instantaneous attachment for these relays. Both the time-delay element and the instantaneous element of these relays were operated from current transformers located in the power-supply line for the transformers. These current transformers had ratios as follows: Alpha I and Alpha II, 20 to 1; and Beta, 10 to 1. In addition the equipment as supplied for Alpha I and Beta was provided with a d-c overload relay operated by the voltage drop across a resistor located in the grounded lead of the high-voltage circuit.

Metering for the output of the decell supply was provided by a d-c milliammeter and a d-c voltmeter. Metering circuits were located at the output of the regulated supply, rather than across the rectifier as in the accell supply, in order that the actual operating voltage and current of the mass spectrograph might be read. In Alpha I both the milliammeter and the voltmeter were operated at the negative voltage of the decell supply. These two meters were mounted on a panel insulated from ground to withstand 50 kv and were protected against surges reflected on the high-voltage transmission line from the mass spectrograph by a choke-coil, capacitor, and Thyrite network. In Alpha II and Beta the meters were located at ground potential. However, it was still necessary to protect the meters from surges as mentioned above.

The ratings of the various component parts of the three accell and the three decell rectifiers that have been described in this chapter are summarized in Table 2.1. For ready comparison of the equipment used in the three processes the table has been broken down into four major headings covering the accell rectifier, the decell rectifier, step-start equipment, and the filament supply.

Table 2.1 — Accell- and Decell-rectifier Equipment Rating

	Alpha I	Alpha II	Beta
Step-start equipment:			
Accell main contactor	3 poles, 25 amp, 600 volts; 110-volt coil	3 poles, 300 amp, 600 volts; 110-volt coil	3 poles, 75 amp, 600 volts; 110-volt coil
Decell main contactor	3 poles, 75 amp, 600 volts; 110-volt coil		3 poles, 75 amp, 600 volts; 110-volt coil
Accell auxiliary contactor	3 poles, 25 amp, 600 volts; 110-volt coil	3 poles, 150 amp, 600 volts; 110-volt coil	3 poles, 25 amp, 600 volts; 110-volt coil
Decell auxiliary contactor	3 poles, 50 amp, 600 volts; 110-volt coil		4 poles, 50 amp, 600 volts; 110-volt coil
Accell resistor (per phase)	8 ohms, 80 watts	1.5 ohms, 180 watts, in parallel (two)	4 ohms, 120 watts
Decell resistor (per phase)	2 ohms, 80 watts		2 ohms, 120 watts
Accell rectifier supply:			
Main transformer	3 phase, 60 cycles, 10 kva, 775/26,500 volts (L to N)	3 phase, 60 cycles, 50 kva, 840/40,600 volts (L to N)	3 phase, 60 cycles, 26.3 kva, 840/44,200 volts (L to N)
Filament transformers	3, each rated single phase, 60 cycles, 0.551 kva, 805/22.5 volts	6, each rated single phase, 60 cycles, 0.551 kva, 805/22.5 volts	3, each rated single phase, 60 cycles, 0.551 kva, 805/22.5 volts
Interphase transformer		180 cycles, 11.5 kva, 23,100-11,500 volts	
Current transformer	2/1 ratio, 3.75-amp secondary	6/1 ratio, 5-amp secondary	3.5/1 ratio, 5-amp secondary
Induction regulator	3 phase, 60 cycles, 5.6 kva, 460 ± 315 volts, 8.5 amp	3 phase, 60 cycles, 24 kva, 460 ± 380 volts, 36.5 amp	3 phase, 60 cycles, 12.2 kva, 460 ± 380 volts, 18.5 amp
Rectifier tubes	Peak anode current, 0.75 amp Peak inverse voltage, 150 kv	Peak anode current, 0.75 amp Peak inverse voltage, 150 kv	Peak anode current, 0.75 amp Peak inverse voltage, 150 kv
Limiter tube		Peak anode current, 7.5 amp Peak inverse voltage, 50 kv	Peak anode current, 7.5 amp Peak inverse voltage, 50 kv
Filter capacitor	0.5 μf, 25 kv d-c	0.2 μf, 50 kv d-c	0.25 μf, 50 kv d-c
Charge and discharge resistor	Charge: 200 ohms, 50 watts Discharge: 400 ohms, 160 watts (one); and 640 ohms, 160 watts (one) in series	Charge: 110 ohms, 458 watts, 2.04 amp Discharge: 110 ohms, 458 watts, 2.04 amp	Charge: 200 ohms, 200 watts Discharge: 400 ohms, 200 watts

Table 2.1—(Continued)

	Alpha I	Alpha II	Beta
Accell rectifier supply:			
Bleeder resistor		6.25 megohms, 8 ma	5 megohms, 10 ma
Voltmeter	10 ma, full scale, calibrated for 50 kv, d-c	2 ma, full scale, calibrated for 50 kv, d-c	10 ma, full scale, calibrated for 50 kv, d-c
Voltmeter resistor	2 megohms, 10 ma	25 megohms, 2 ma	5 megohms, 10 ma
Ammeter	500 ma, d-c full scale	750 ma, d-c, full scale	500 ma, d-c, full scale
Terminating resistor		Four in series, each rated 5.5 ohms, 1,000 watts	Four in series, each rated 6.25 ohms, 1,000 watts
Terminating capacitor (line to ground)		0.025 μf, 50 kv, d-c	0.025 μf, 50 kv, d-c
Terminating capacitor (line to line)		5 μf, 1,000 volts, d-c	
Decell rectifier supply:			
Main transformer	3 phase, 60 cycles, 51.5 kva 575/42,000-2,100 volts (L to N)	3 phase, 60 cycles, 117 kva, 620/41,400 volts (L to L)	3 phase, 60 cycles, 51.5 kva, 575/42,000-21,000 volts (L to N)
Filament transformer	6, each rated single phase, 60 cycles, 0.551 kva, 805/22.5 volts	3 phase, 60 cycles, 7.17 kva, 840/39.8 (L to L), 23 volts (L to N)	6, each rated 3 phase, 60 cycles, 0.55 kva, 805/22.5 volts
Current transformer	20/1 ratio, 5-amp secondary	20/1 ratio, 5-amp secondary	10/1 ratio, 5-amp secondary
Interphase transformer	Single phase, 180 cycles, 11.5 kva, 23,100-11,500 volts		Single phase, 180 cycles, 11.5 kva, 23,100-11,500 volts
Induction regulator	3 phase, 60 cycles, 10.3 kva, 460 ± 115 volts, 51.7 amp	3 phase, 60 cycles, 30.2 kva, 460 ± 160 volts, 109 amp	3 phase, 60 cycles, 10.3 kva, 460 ± 115 volts, 51.7 amp
Rectifier tubes	Peak anode current, 0.75 amp Peak inverse voltage, 150 kv	Peak anode current, 7.5 amp Peak inverse voltage, 50 kv	Peak anode current, 0.75 amp Peak inverse voltage, 150 kv
Limiter tube	Peak anode current, 7.5 amp Peak inverse voltage, 50 kv		
Regulator tube	Peak anode current, 7.5 amp Peak forward voltage, 40 kv Amplification factor, 36	Two in parallel, each rated: Peak anode current, 7.5 amp Peak forward voltage, 40 kv Amplification factor, 36	Peak anode current, 7.5 amp Peak forward voltage, 40 kv Amplification factor, 36
Filter capacitor	Three in parallel, each rated 0.25 μf, 50 kv, d-c	Three in parallel, each rated 0.2 μf, 50 kv, d-c	Four in parallel, each rated 0.25 μf, 50 kv, d-c

Table 2.1 — (Continued)

	Alpha I	Alpha II	Beta
Decell rectifier supply:			
Charge and discharge resistor	Charge: 200 ohms, 200 watts Discharge: 615 ohms, 200 watts	Charge: three in series, each rated 71 ohms, 468 watts, 2.57 amp Discharge: three in series, each rated 71 ohms, 468 watts, 2.57 amp	Charge: 200 ohms, 200 watts Discharge: 200 ohms, 200 watts
Voltmeter	10 ma, full scale, calibrated for 50 kv, d-c	2 ma, full scale, calibrated for 50 kv, d-c	10 ma, full scale, calibrated for 50 kv, d-c
Voltmeter resistor	5 megohms, 10 ma	25 megohms, 2 ma	5 megohms, 10 ma
Ammeter	1.5 amp, d-c, full scale	3 amp, d-c, full scale	1.5 amp, d-c, full scale
Terminating resistor	Four in series, each rated 6.25 ohms, 1,000 watts	Eight in series, each rated 3.5 ohms, 750 watts	Four in series, each rated 6.25 ohms, 1,000 watts
Terminating capacitor	0.025 μf, 50 kv, d-c, insulated from case for 30 kv, d-c	0.025 μf, 50 kv, d-c	0.025 μf, 50 kv, d-c, insulated from case for 30 kv, d-c
Filament supply:			
Contactor (rectifier filament)	3 poles, 15 amp, 460 volts; 110-volt coil	3 poles, 50 amp, 600 volts; 110-volt coil	3 poles, 15 amp, 600 volts; 115-volt coil
Breaker		Magnetic; 35 amp, 460 volts	
Contactor (regulator and limiter tube)	3 poles, 15 amp, 460 volts; 110-volt coil		3 poles, 15 amp, 600 volts; 110-volt coil
Breaker (regulator and limiter tube)	3 poles, 20 amp, 460 volts; thermal trip		3 poles, 20 amp, 460 volts; thermal trip
Induction regulator (rectifier filament)	3 phase, 60 cycles, 2.25 kva, 460 ± 345 volts, 3.76 amp	3 phase, 60 cycles, 11.3 kva, 460 ± 380 volts, 17.2 amp	3 phase, 60 cycles, 2.44 kva, 460 ± 345 volts, 3.76 amp
Induction regulator (limiter tube)	Single phase, 60 cycles, 0.507 kva, 460 ± 362 volts, 1.4 amp	Single phase, 60 cycles, 0.225 kva, 840 ± 80 volts, 2.68 amp	Single phase, 60 cycles, 5.07 kva, 460 ± 362 volts, 1.4 amp
Induction regulator (regulator tube)	3 phase, 60 cycles, 2.25 kva, 460 ± 345 volts, 3.76 amp	3 phase, 60 cycles, 1 kva, 770 ± 154 volts, 3.76 amp	3 phase, 60 cycles, 2.24 kva, 460 ± 345 volts, 3.7 amp
Auto transformer	3 phase, 60 cycles, 1.758 kva, Y connected, 805 volts (L to L); from 660 (L to L) to 987 volts (L to L)	3 phase, 60 cycles, 11.85 kva, delta connected 840 volts (L to L); range 840 (L to L) to 640 volts (L to L)	3 phase, 60 cycles, 1.758 kva, Y connected, 805 volts (L to L); range 660 (L to L) to 987 volts (L to L)
Transformer (limiter tube)	Single phase, 60 cycles, 1.14 kva, 822/23-11.5 volts	Single phase, 60 cycles, 1 kva, 920/21-10.5 volts	Single phase, 60 cycles, 1.14 kva, 822/23-11.5 volts
Transformer (regulator tube)	3 phase, 60 cycles, 4.21 kva, 805/20 (L to L), 11.55 (L to N) volts	3 phase, 60 cycles, 3 kva, 920/14.5 (L to L), 8.37 (L to N) volts	3 phase, 60 cycles, 4.21 kva, 805/20 (L to L), 11.55 (L to N) volts

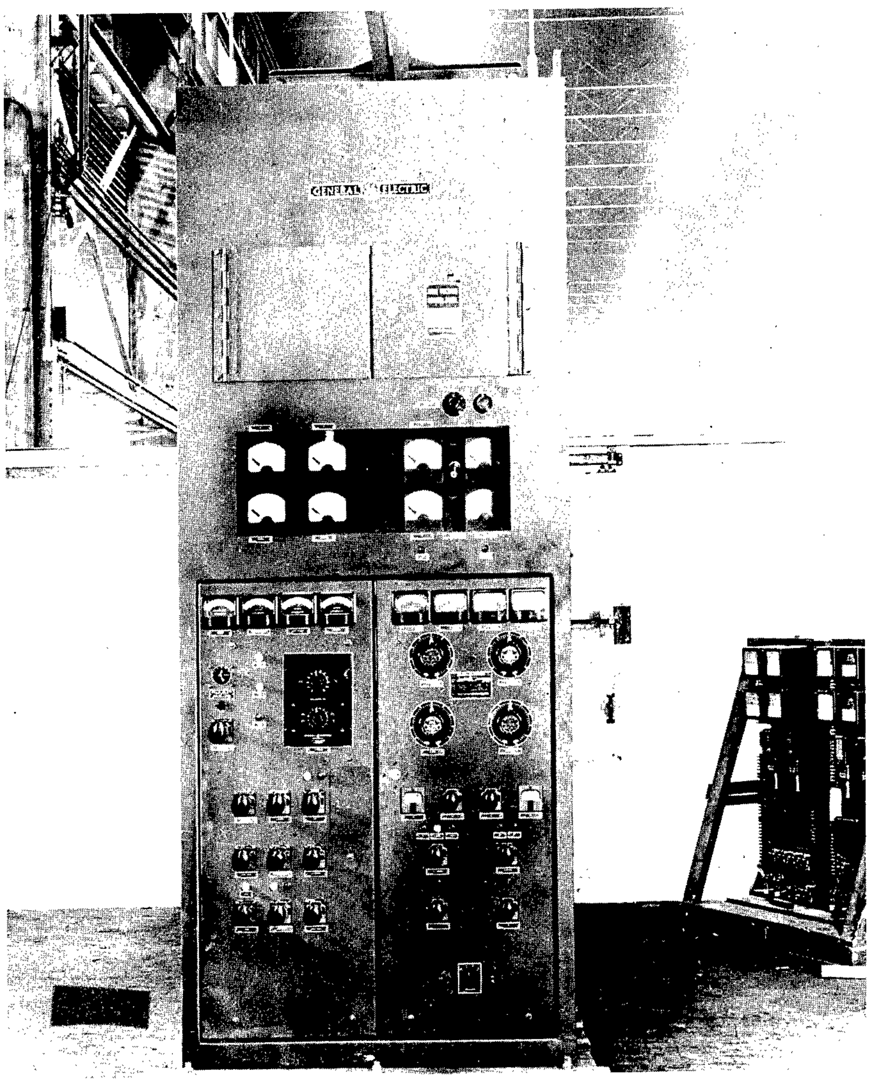


Fig. 2.1 — Alpha I high-voltage cubicle, front view showing operator's panel.

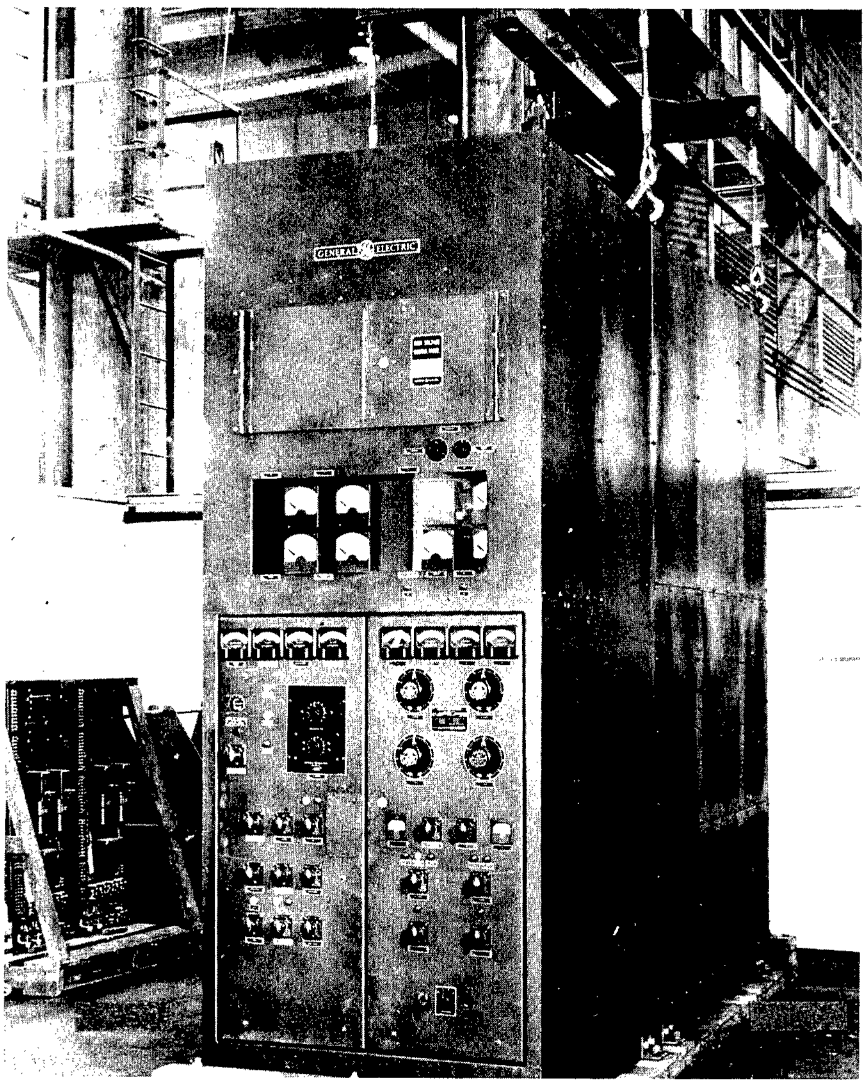


Fig. 2.2 — Alpha I high-voltage cubicle, front and side view.

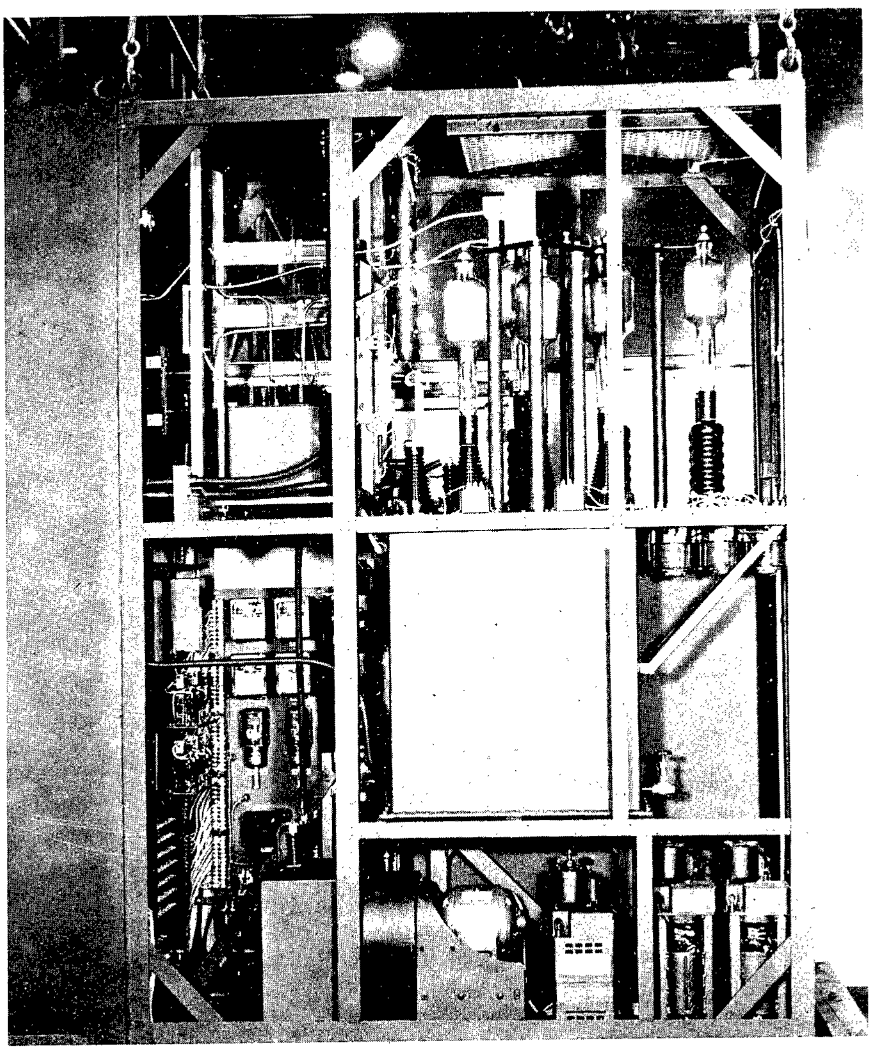


Fig. 2.3—Alpha I high-voltage cubicle, right side of rear section with casing removed.

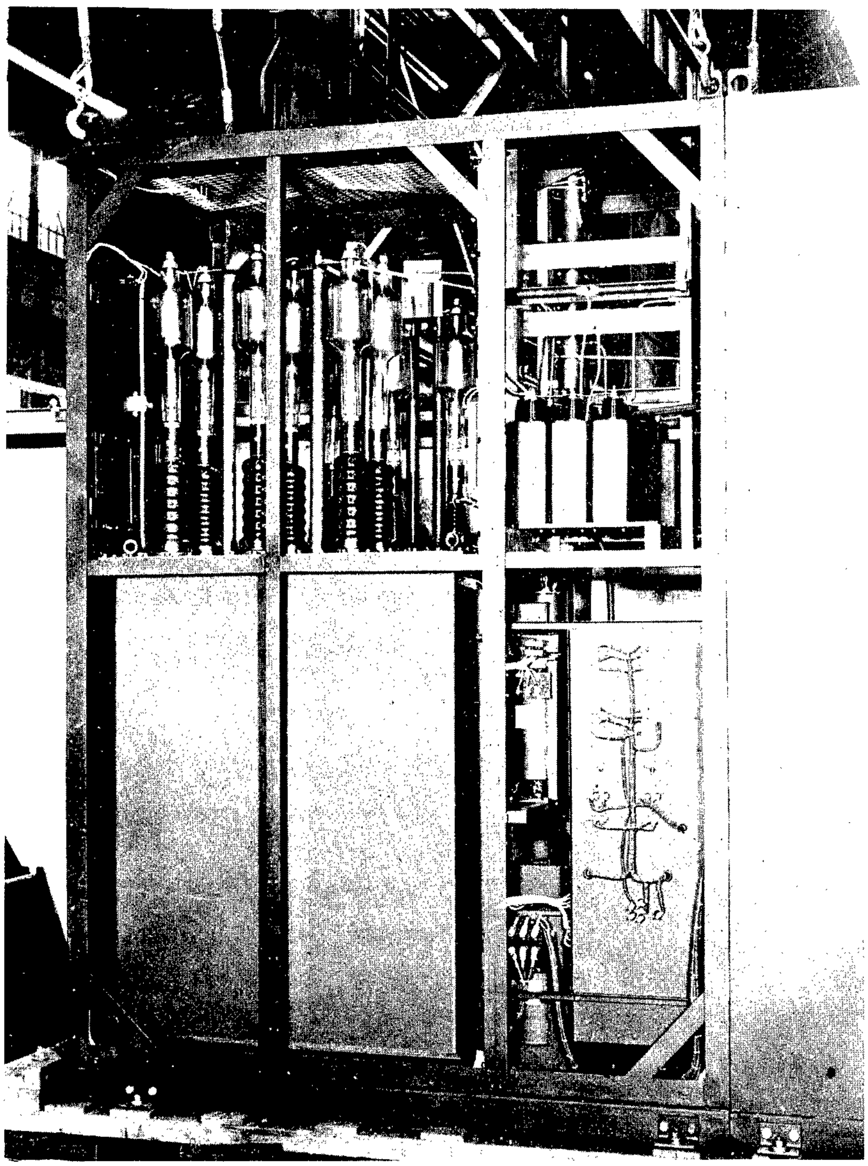


Fig. 2.4—Alpha I high-voltage cubicle, left side of rear section with casing removed.

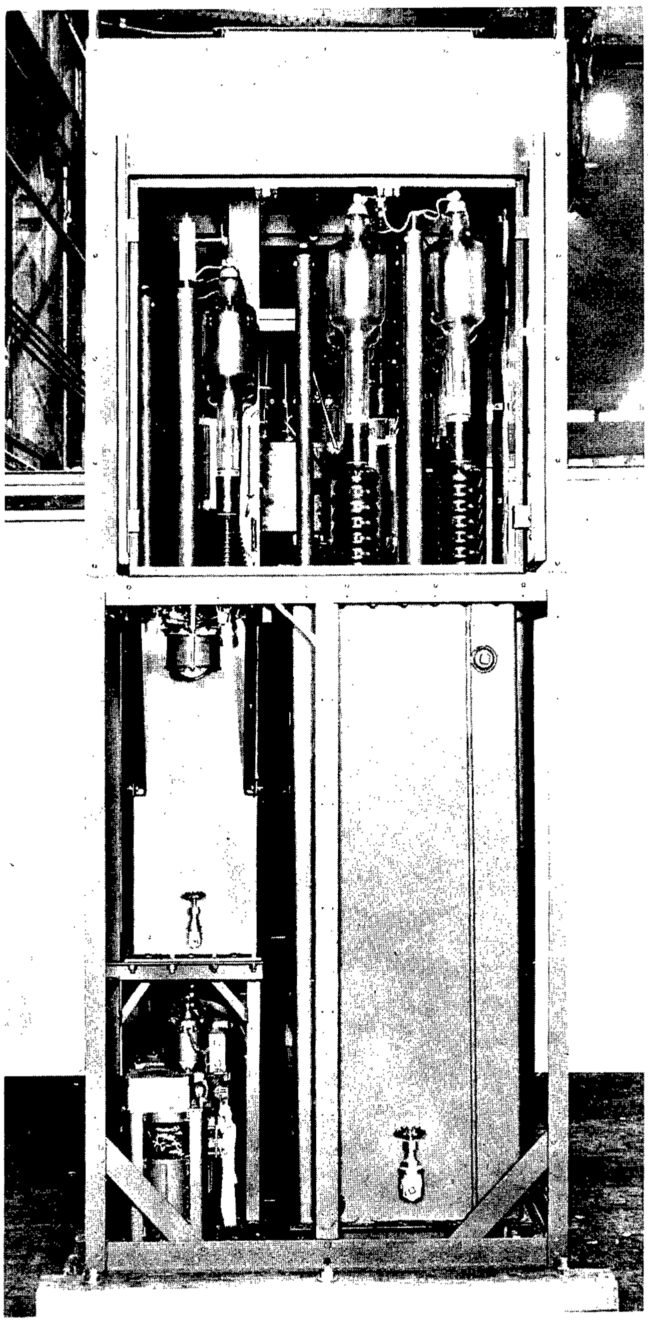


Fig. 2.5—Alpha I high-voltage cubicle, rear view with casing removed and doors open.

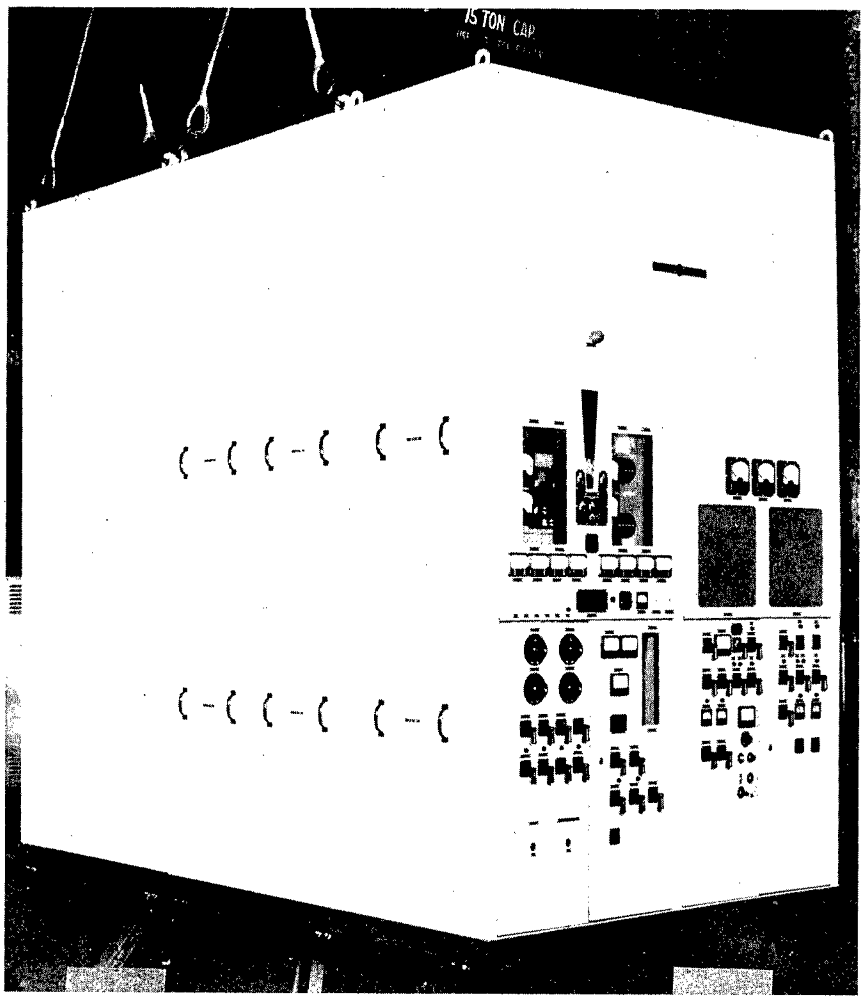


Fig. 2.6 — Alpha II high-voltage and heater cubicle, oblique left front view.

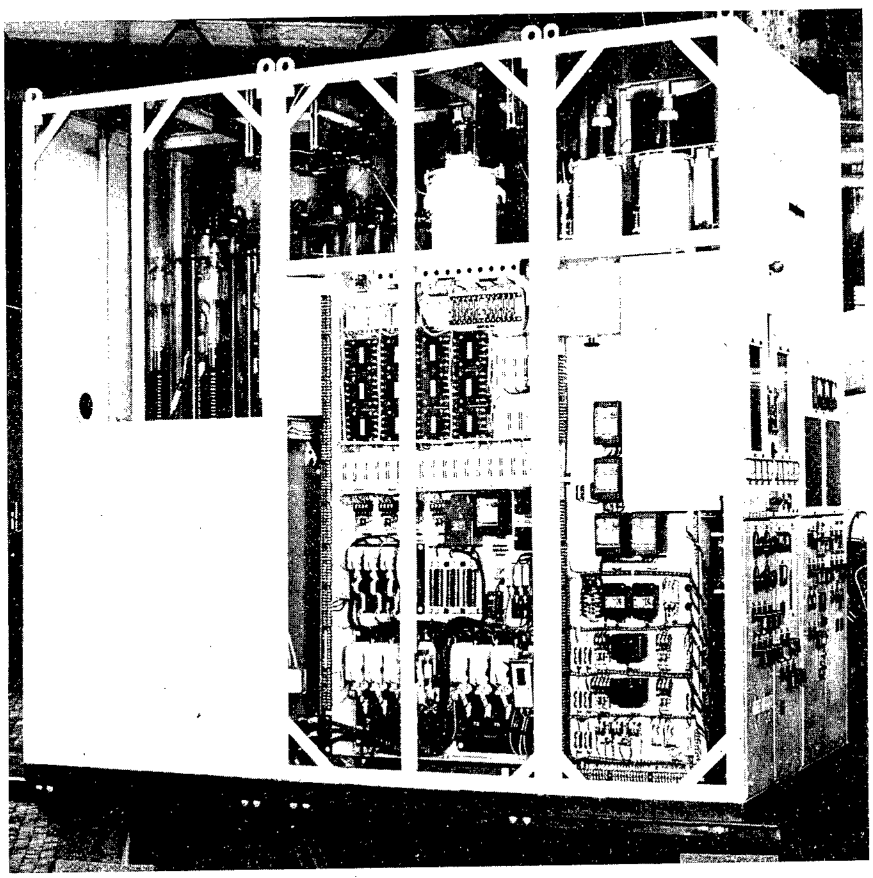


Fig. 2.7—Alpha II high-voltage and heater cubicle, oblique view of left side with covers removed.

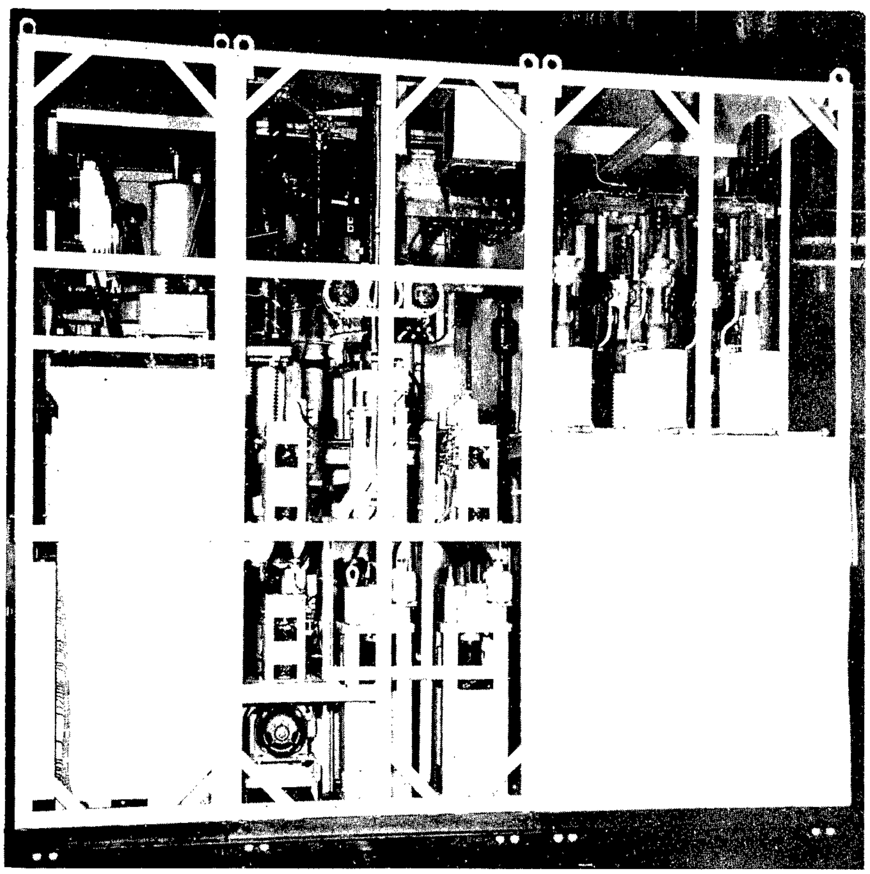


Fig. 2.8—Alpha II high-voltage and heater cubicle, right-side view with covers removed.

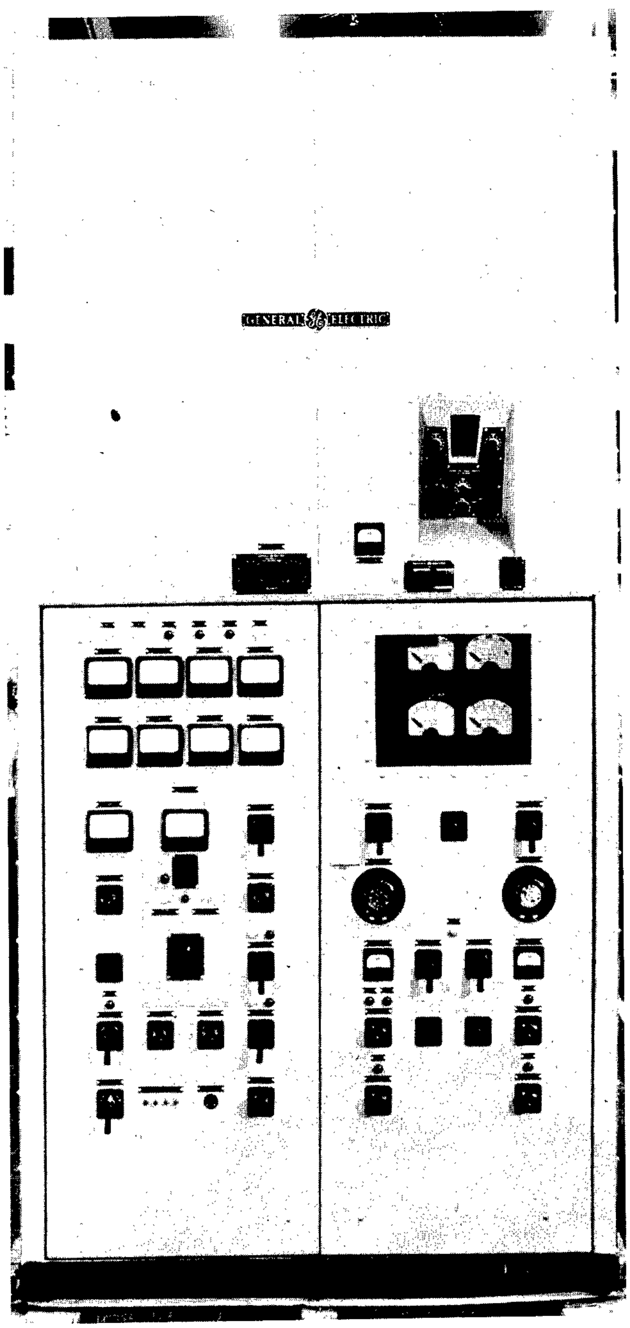


Fig. 2.9—Beta high-voltage cubicle.

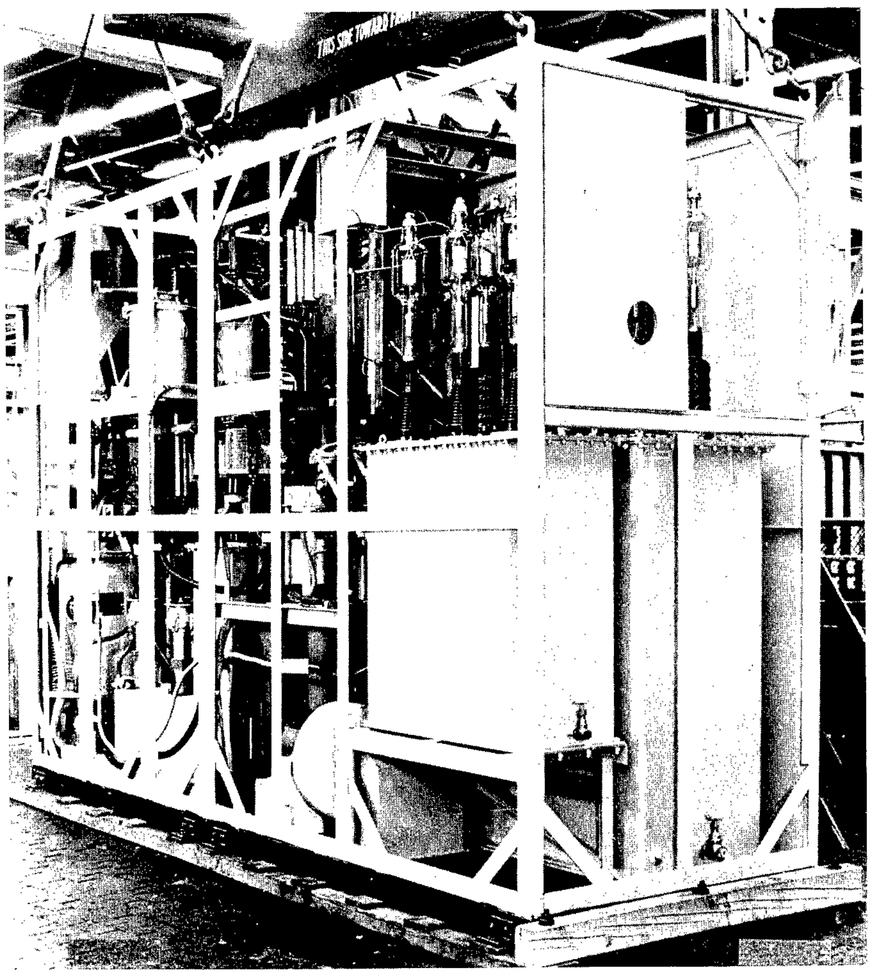


Fig. 2.10—Beta high-voltage cubicle, oblique view of rear and right side with casing removed.

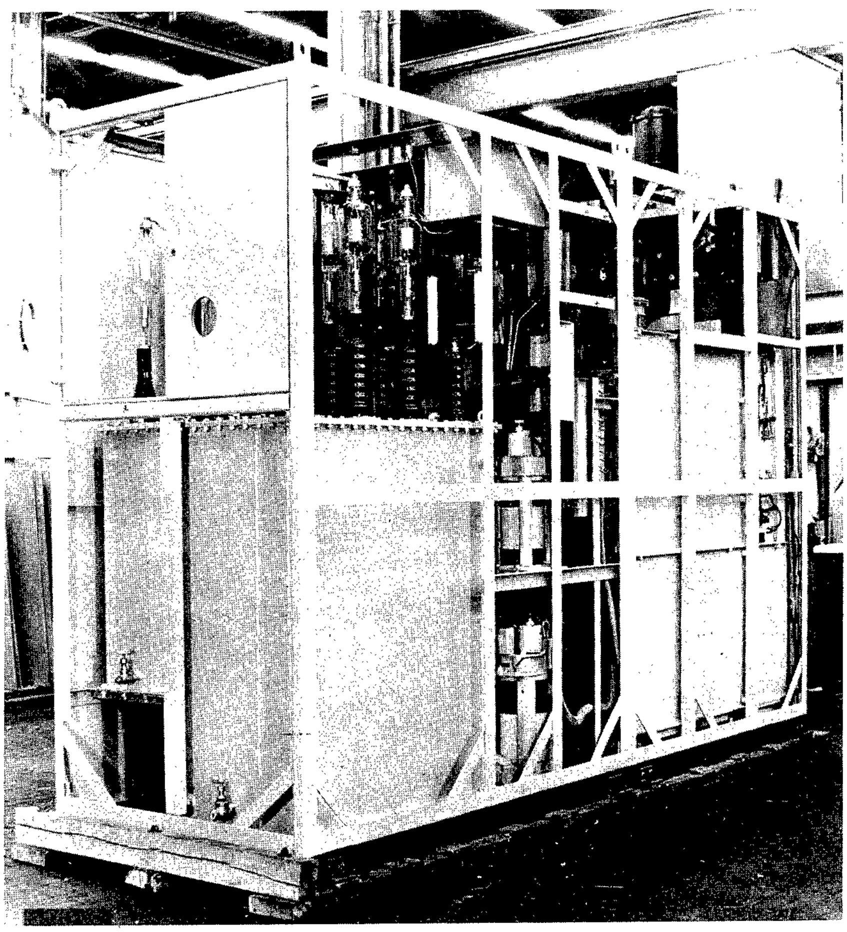


Fig. 2.11—Beta high-voltage cubicle, oblique view of left side and rear with casing removed.

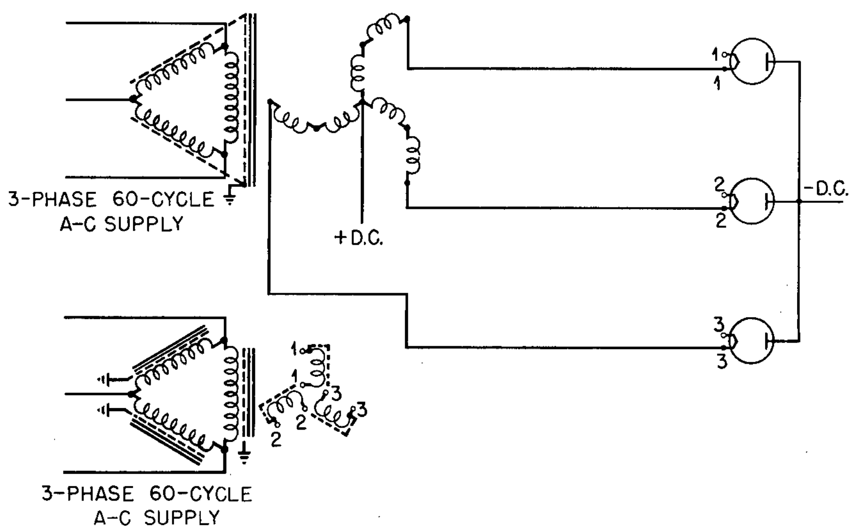


Fig. 2.12 — Schematic diagram of the Alpha I and Beta accell rectifiers. Filament transformer: 60 cycles, single phase, 0.551 kva, 805/22.5 volts. Rectifier tubes: General Electric KC-4 or equal. Rectifier transformer: Alpha I, 3-phase 60-cycle 10-kva 775-volt delta primary and 26,500-volt (line to neutral) secondary; Beta, 3-phase 60-cycle 26.3-kva 840-volt delta primary and 44,200-volt (line to neutral) secondary.

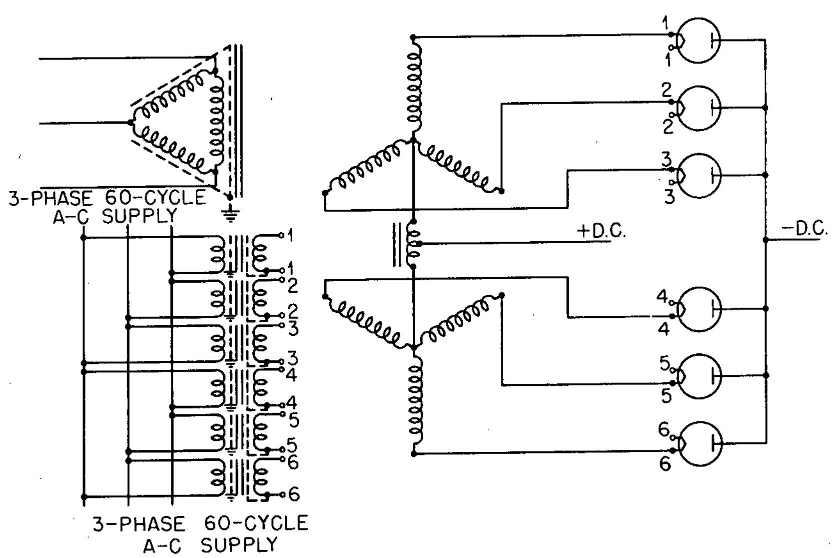


Fig. 2.13 — Schematic diagram of the Alpha II accell, Alpha I decell, and Beta decell rectifiers. Filament transformer: 60 cycles, single phase, 0.551 kva, 805/22.5 volts. Rectifier tubes: General Electric KC-4 or equal. Rectifier transformer: Alpha II accell, 3-phase 60-cycle 50-kva 840-volt delta primary and 40,600-volt (line to neutral) secondary; Alpha I and Beta decell, 3-phase 60-cycle 51.5-kva 575-volt delta primary and 42,000-volt (line to neutral) secondary.

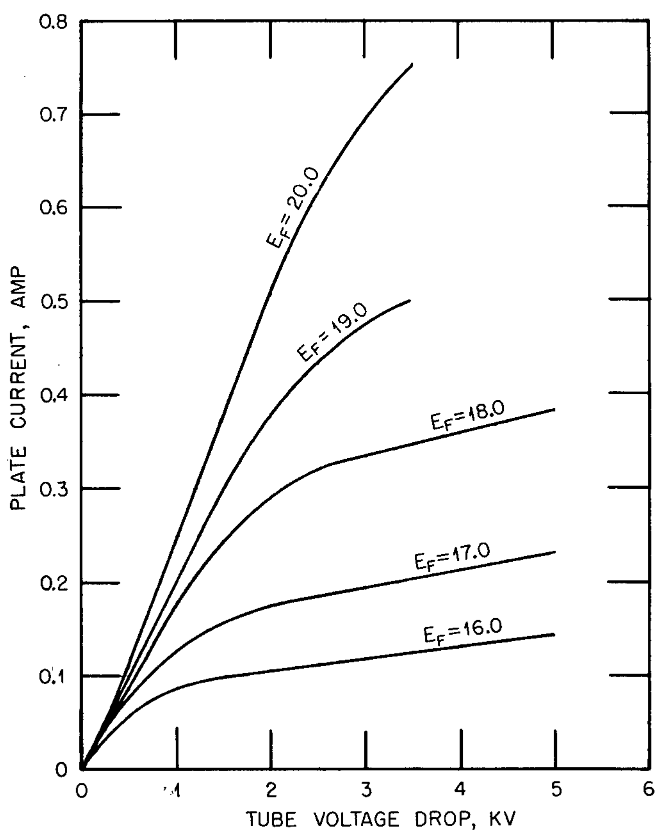


Fig. 2.14 — Characteristic curves for General Electric KC-4 rectifier tube. E_F is the filament voltage.

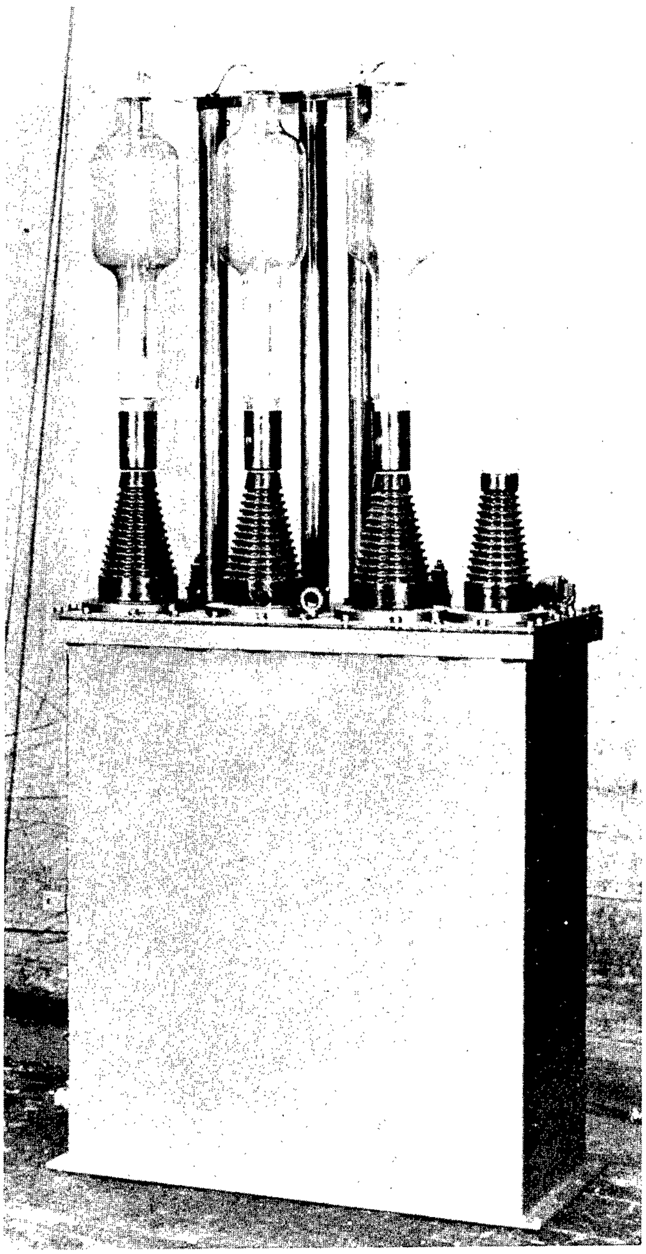


Fig. 2.15 — Alpha I accell-rectifier transformer unit.

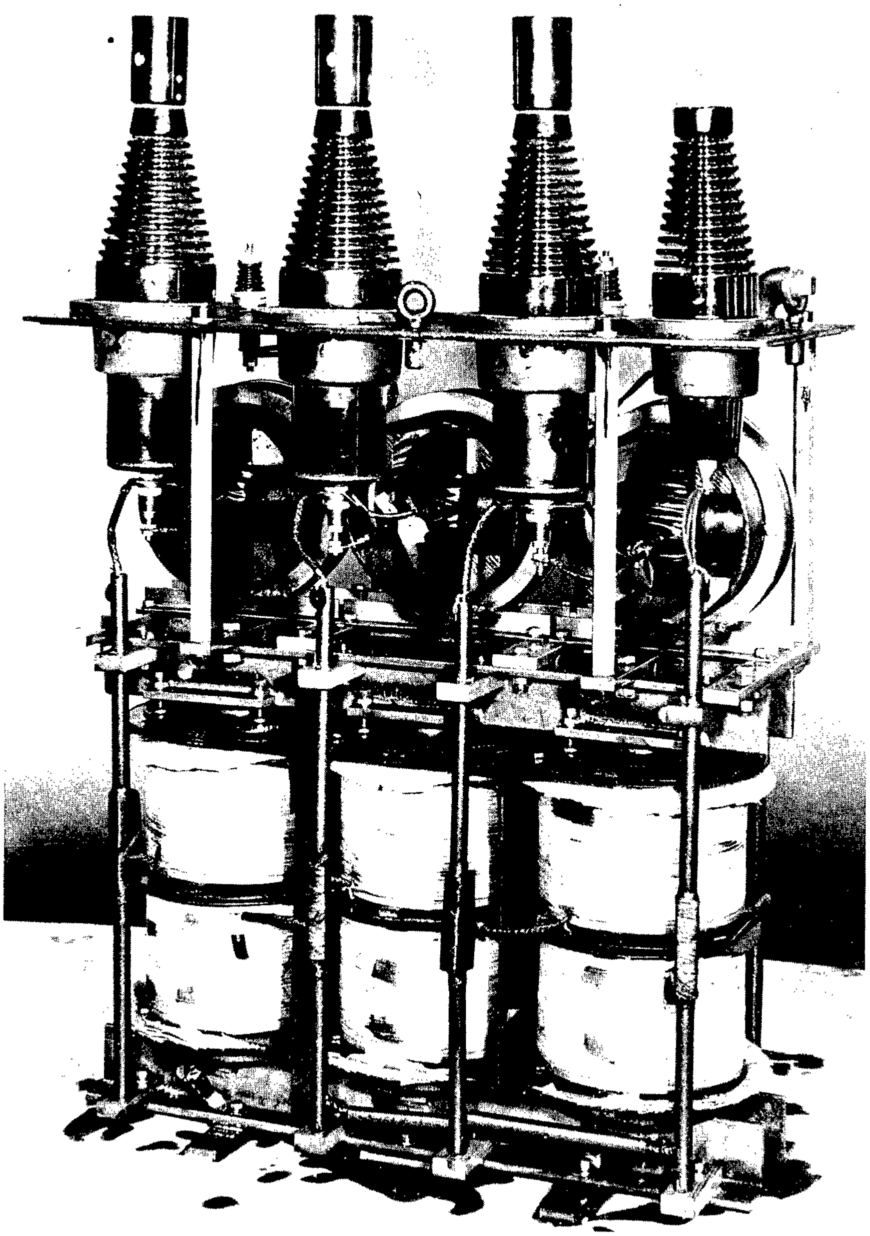


Fig. 2.16 — Alpha I accell-rectifier transformer unit, oblique view of high-voltage side with tank removed.

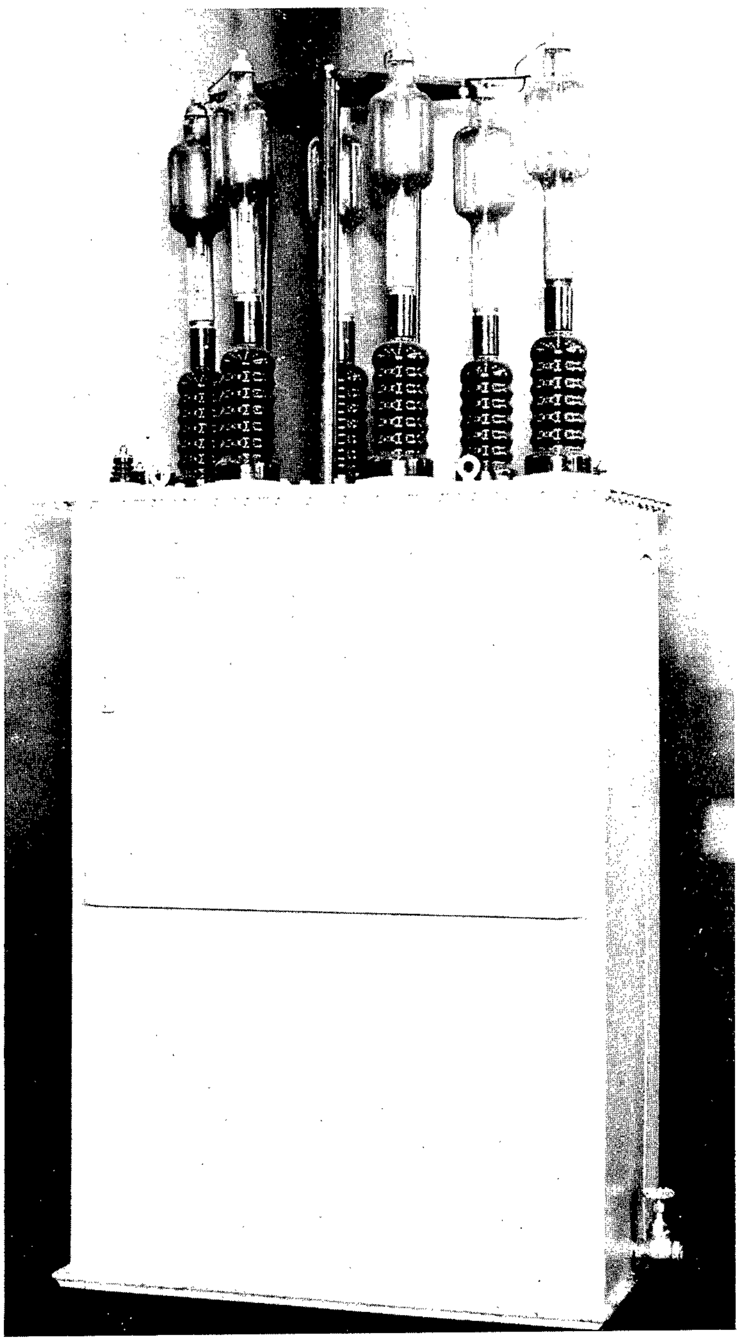


Fig 2.17 — Alpha II accell-rectifier transformer unit.

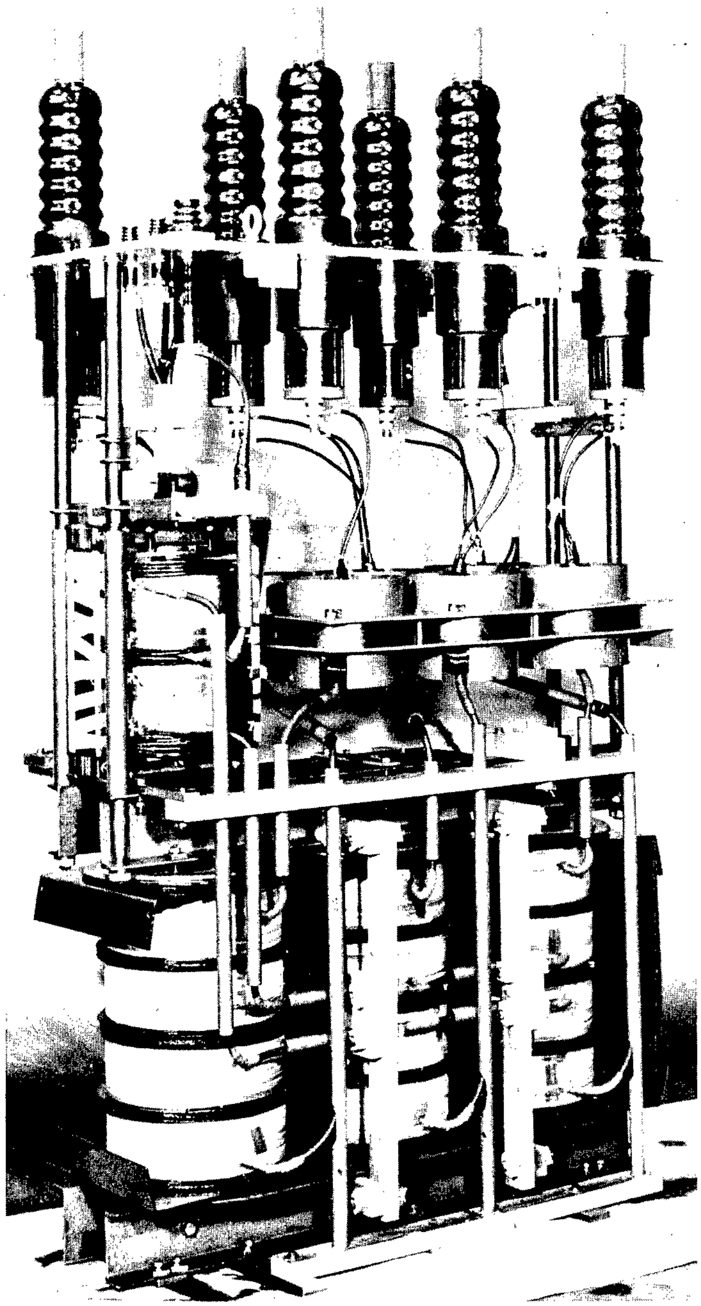


Fig. 2.18 — Alpha II accell-rectifier transformer unit, oblique view of high-voltage side with tank removed.

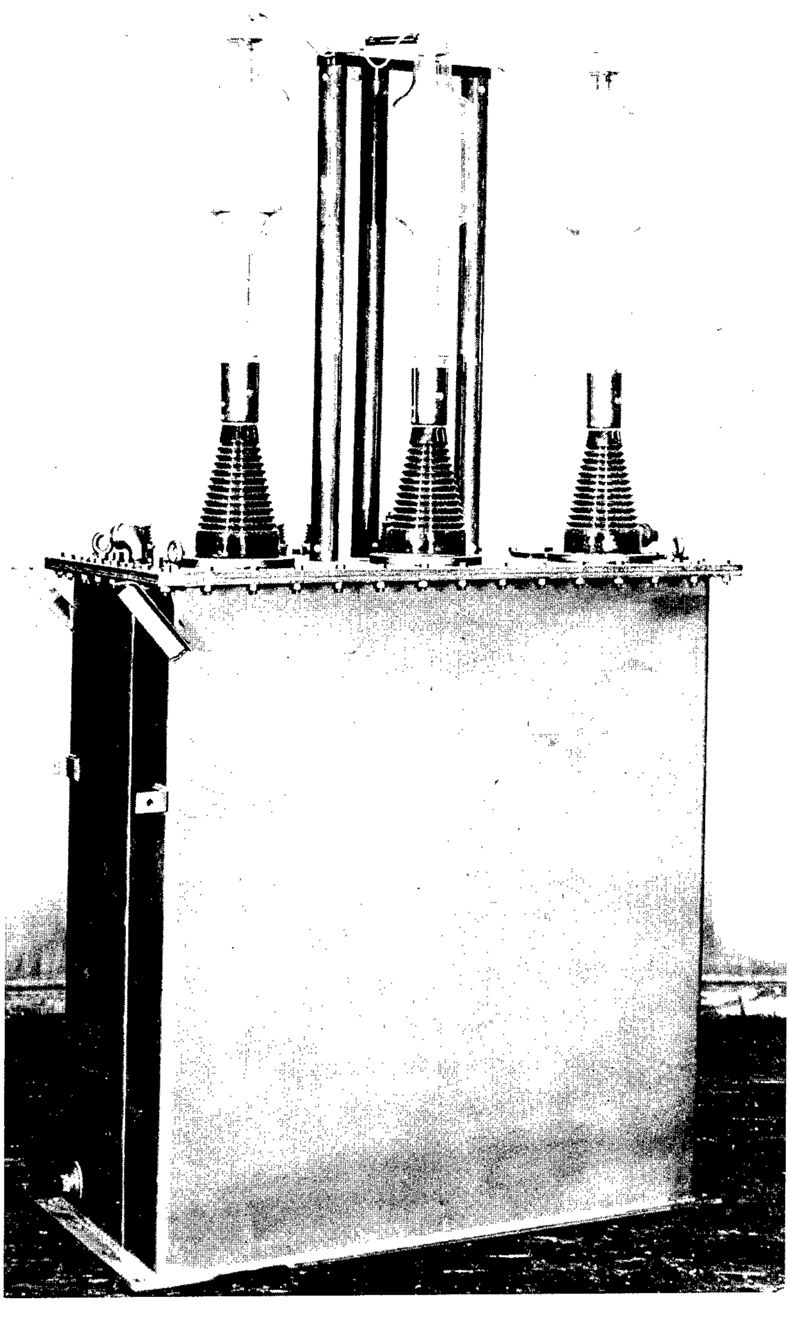


Fig. 2.19 — Beta accell-rectifier transformer unit.

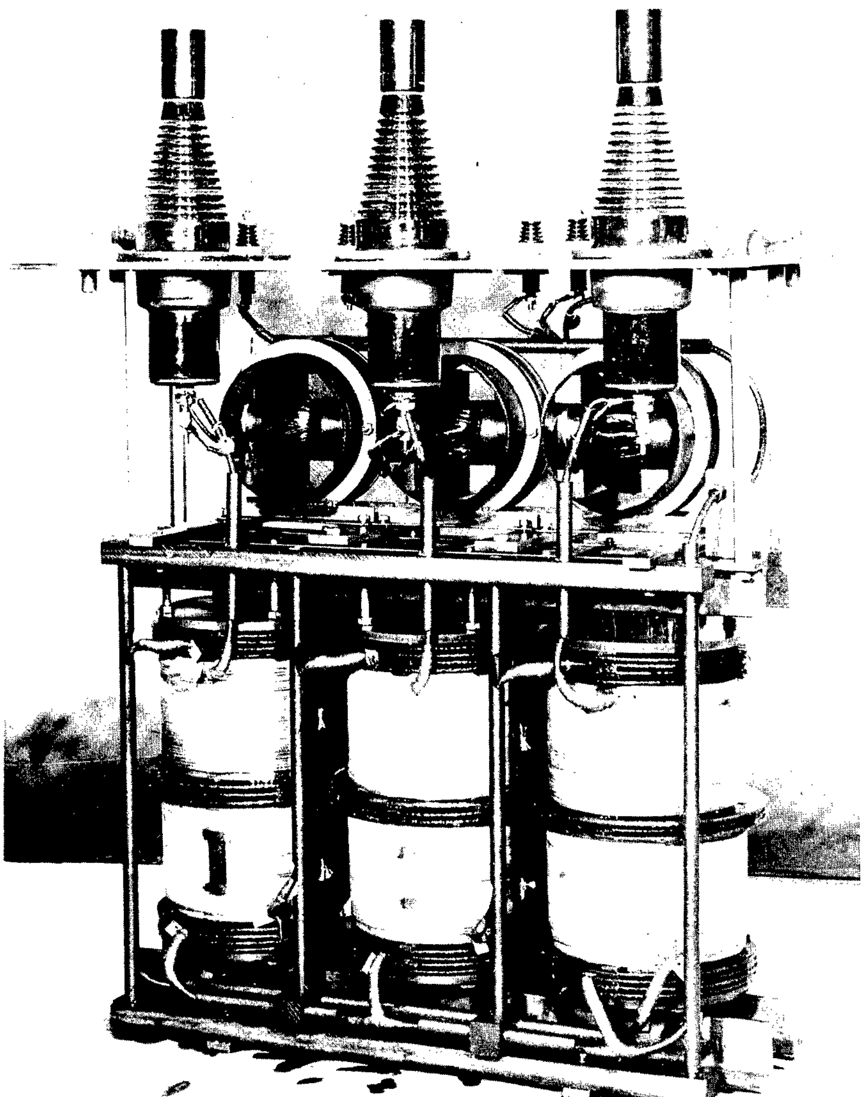


Fig. 2.20 — Beta accell-rectifier transformer unit, oblique view of high-voltage side with tank removed.

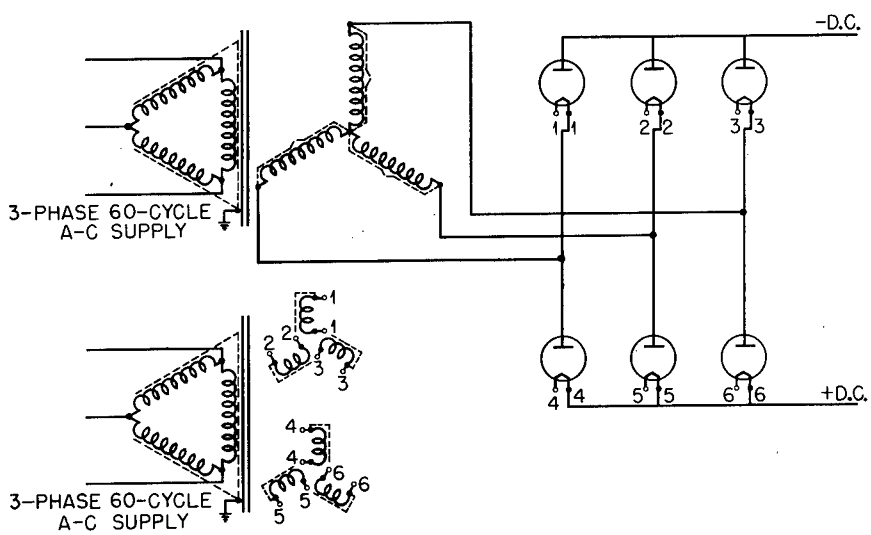


Fig. 2.21—Schematic diagram of the Alpha II decell rectifier. Rectifier transformer: 3-phase 60-cycle 117-kva 620-volt delta primary and 41,400-volt (line to line) secondary; filament transformer: 3-phase 60-cycle 7.17-kva 804-volt delta primary and 23-volt (line to neutral) secondary; rectifier tubes: General Electric GL-605 or equal.

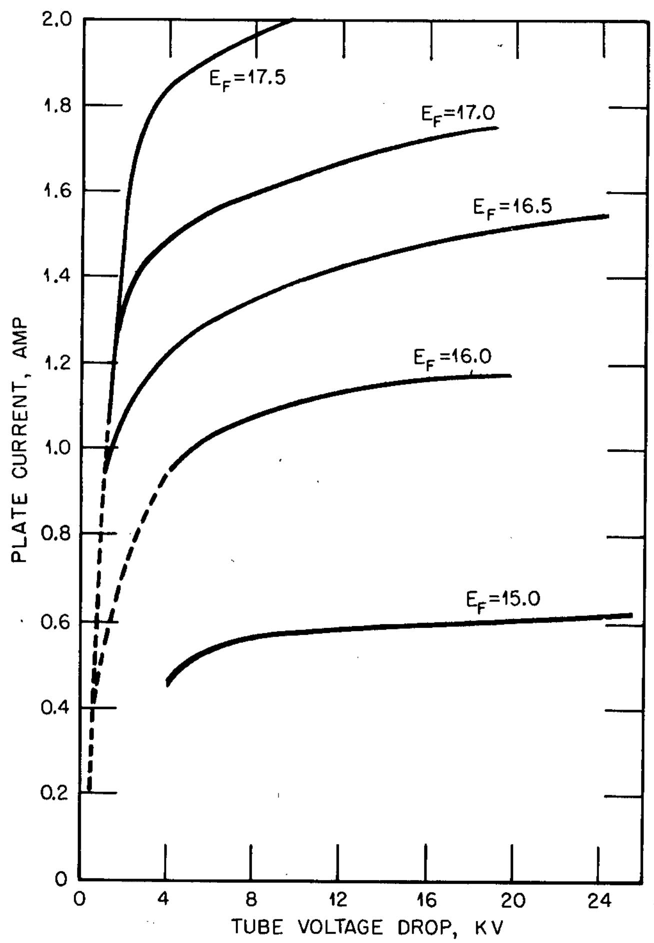


Fig. 2.22 — Characteristic curves for General Electric GL-605 rectifier tube. E_F i the filament voltage.

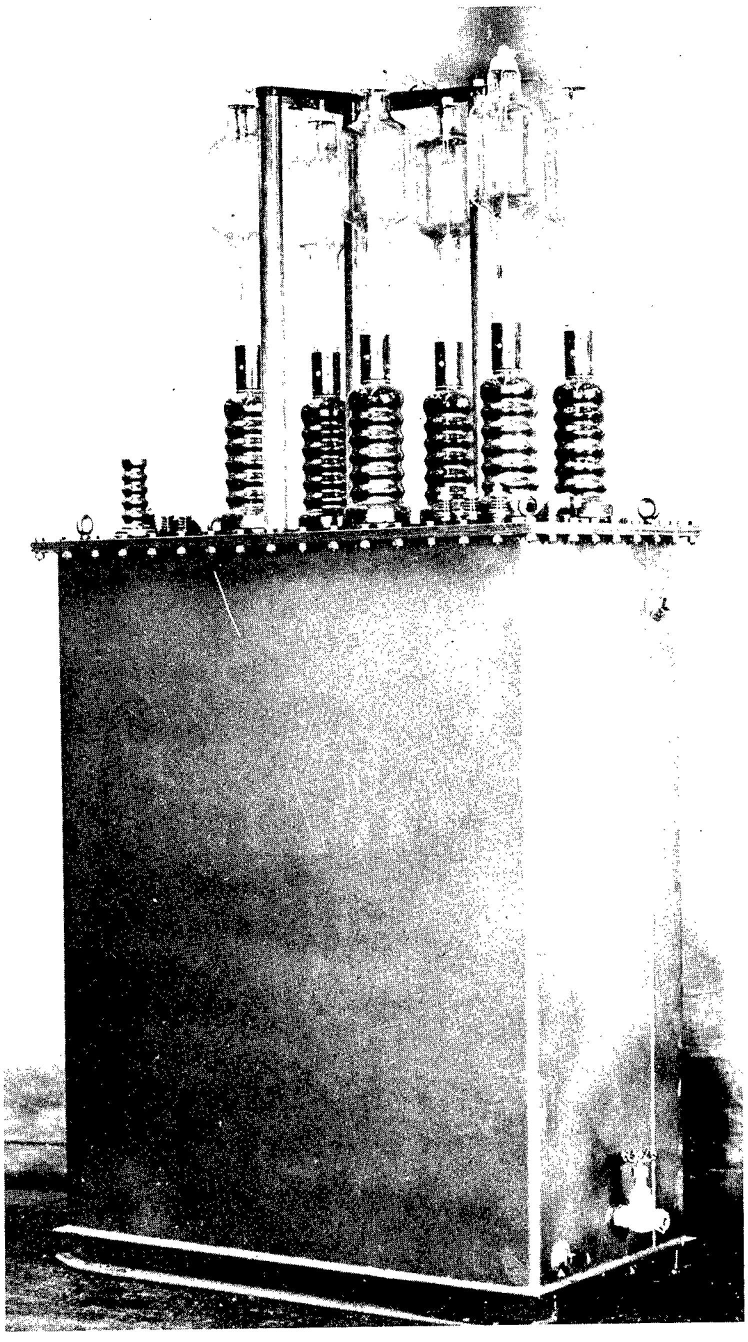


Fig. 2.23 — Alpha I decell-rectifier transformer unit.

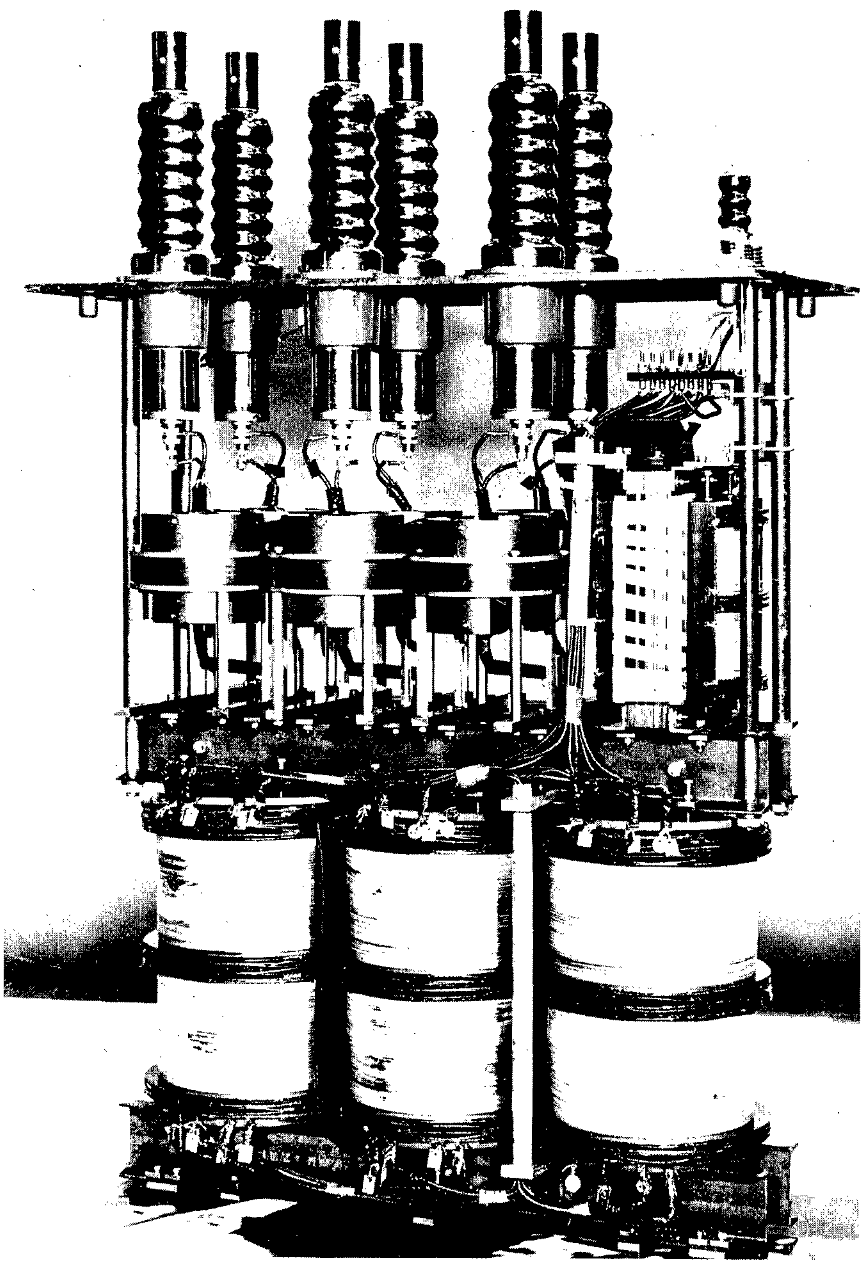


Fig. 2.24 — Alpha I decell-rectifier transformer unit, oblique view of low-voltage side with tank removed.

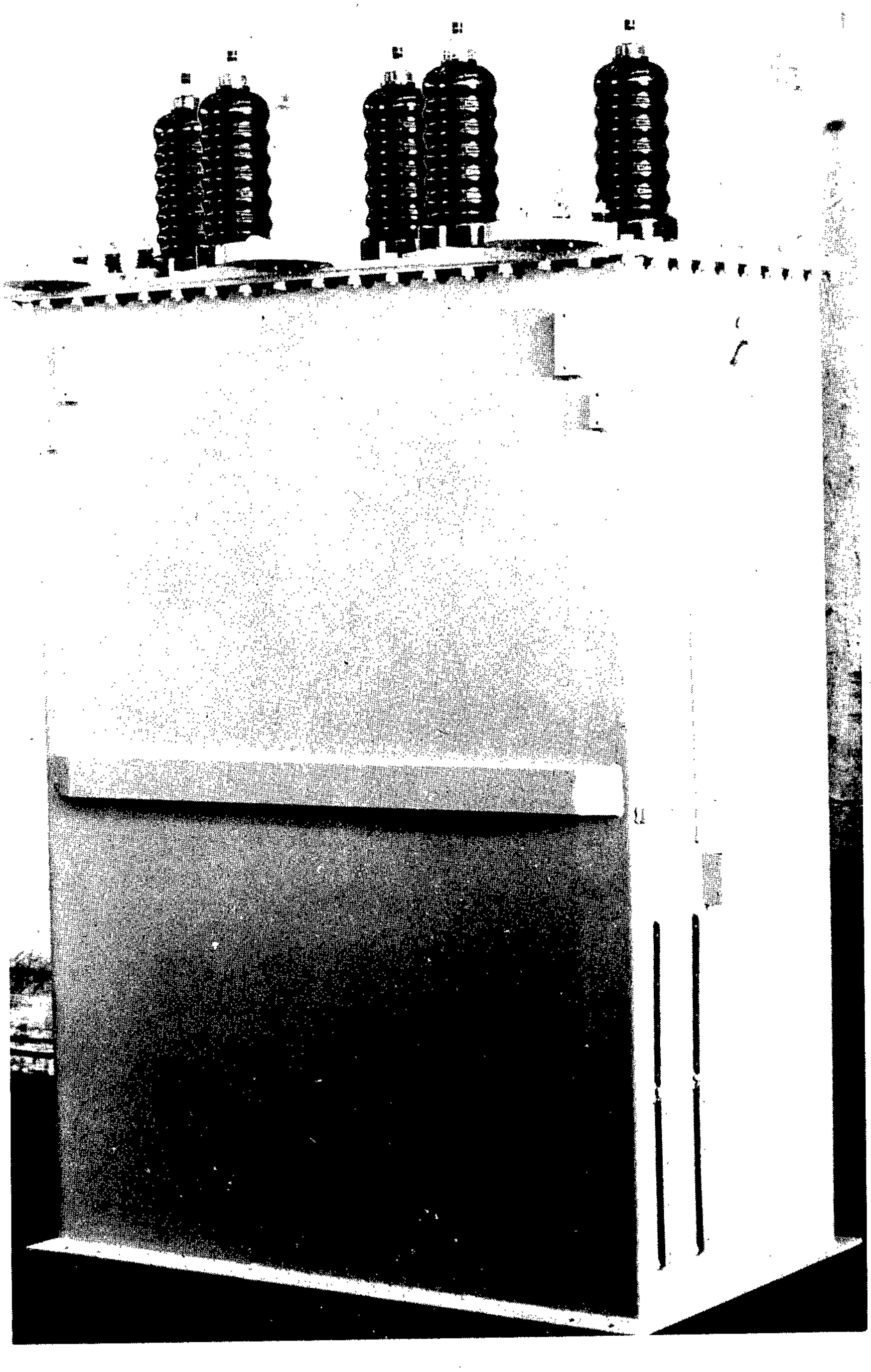


Fig. 2.25 — Alpha II decell-rectifier transformer.

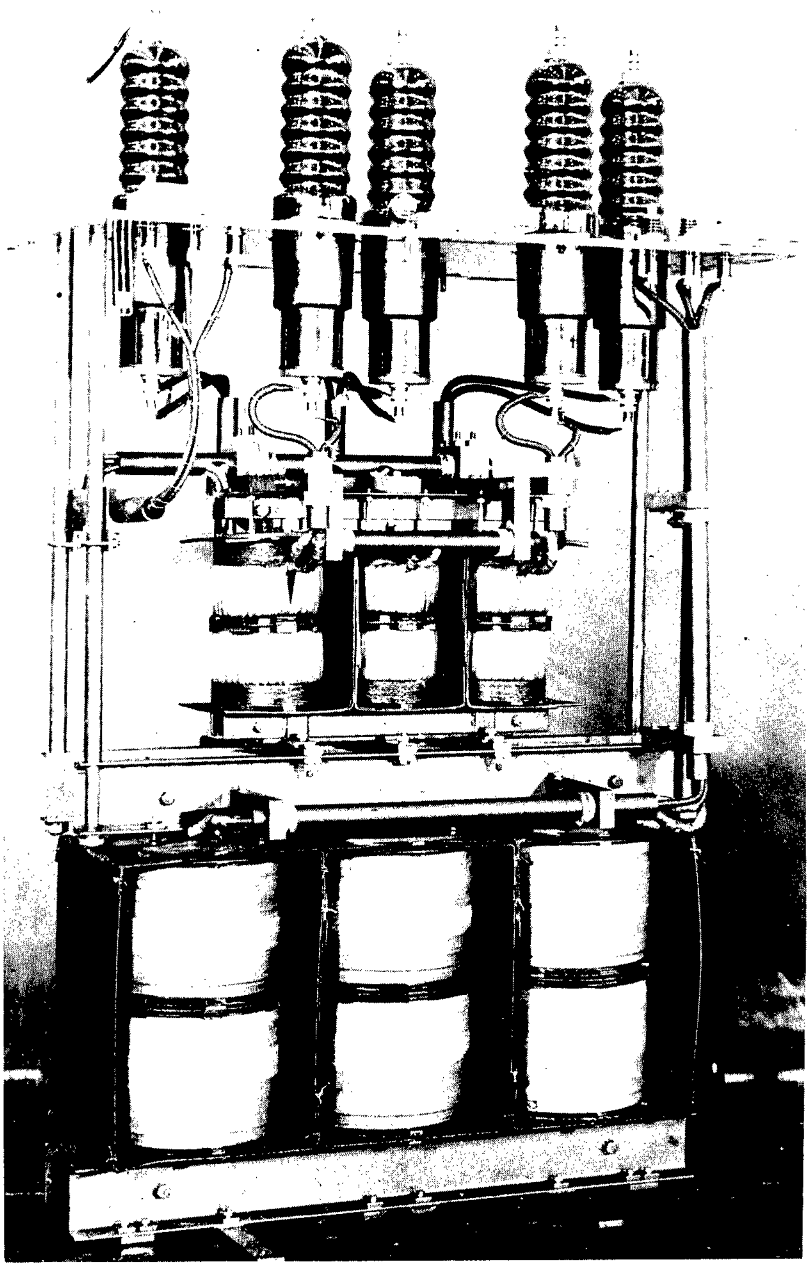


Fig. 2.26—Alpha II decell-rectifier transformer, oblique view of low-voltage side with tank removed.

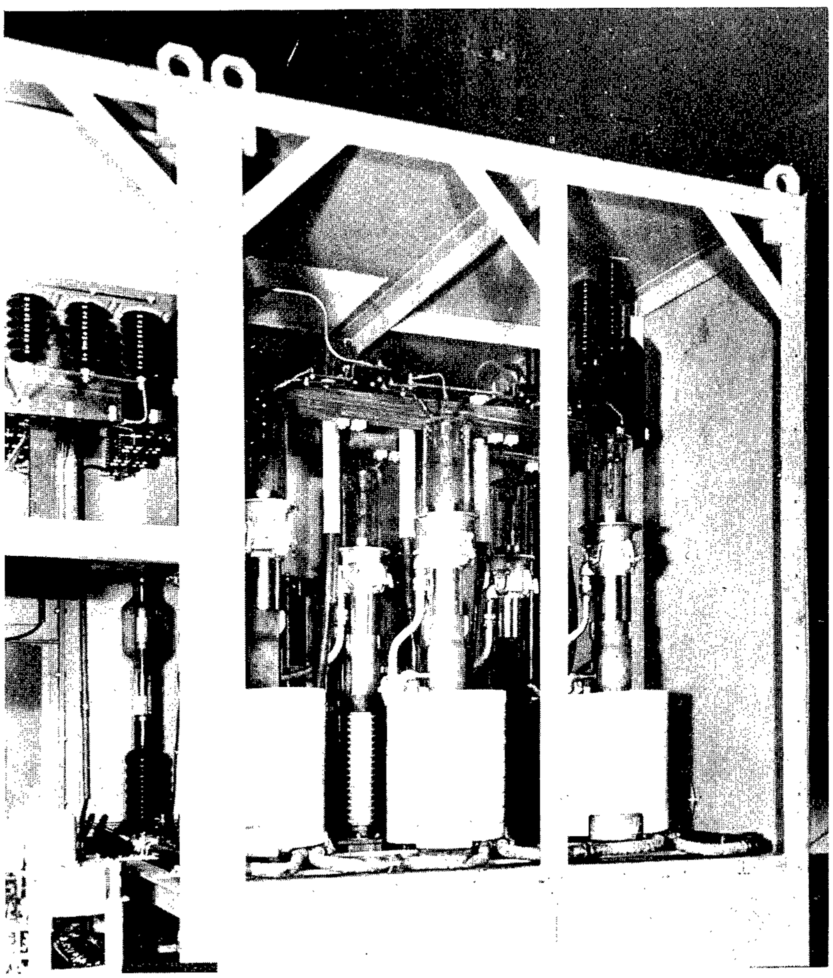


Fig. 2.27—Alpha II high-voltage cubicle, interior view of rear section from right side showing the decell-rectifier tube arrangement.

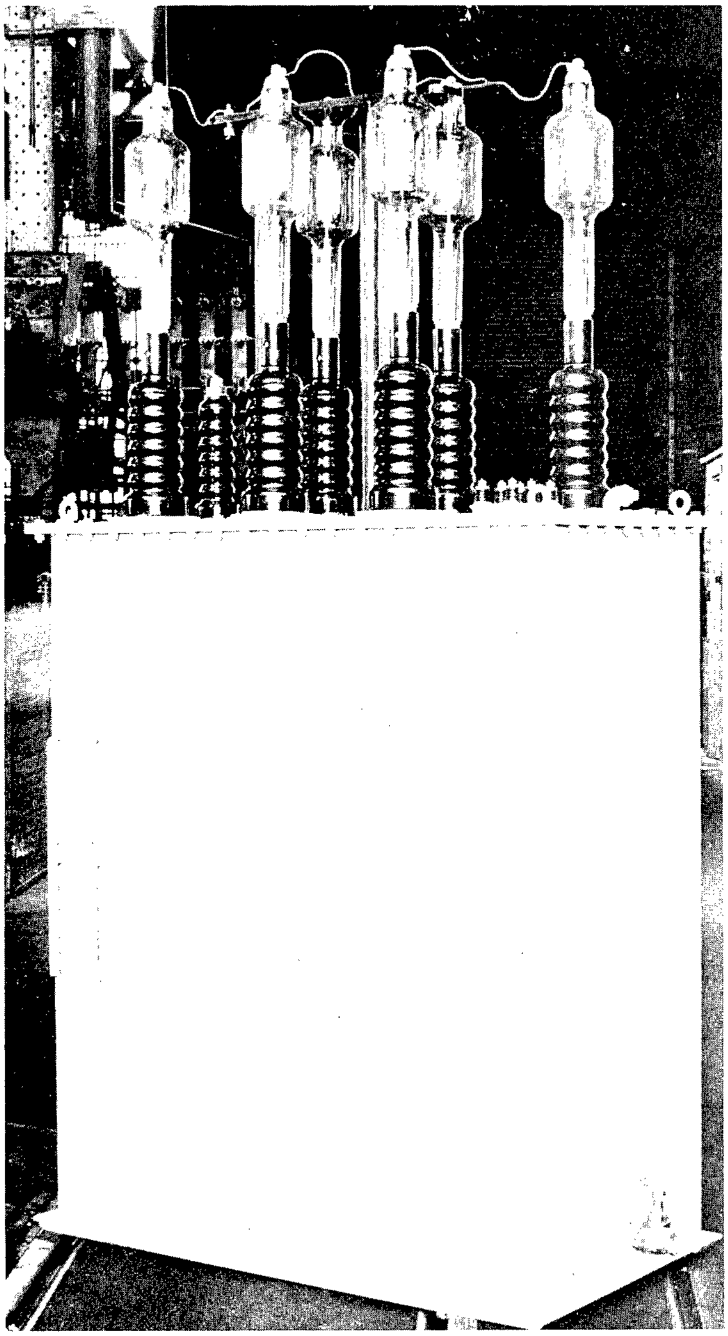


Fig. 2.28 —Beta decell-rectifier transformer unit.

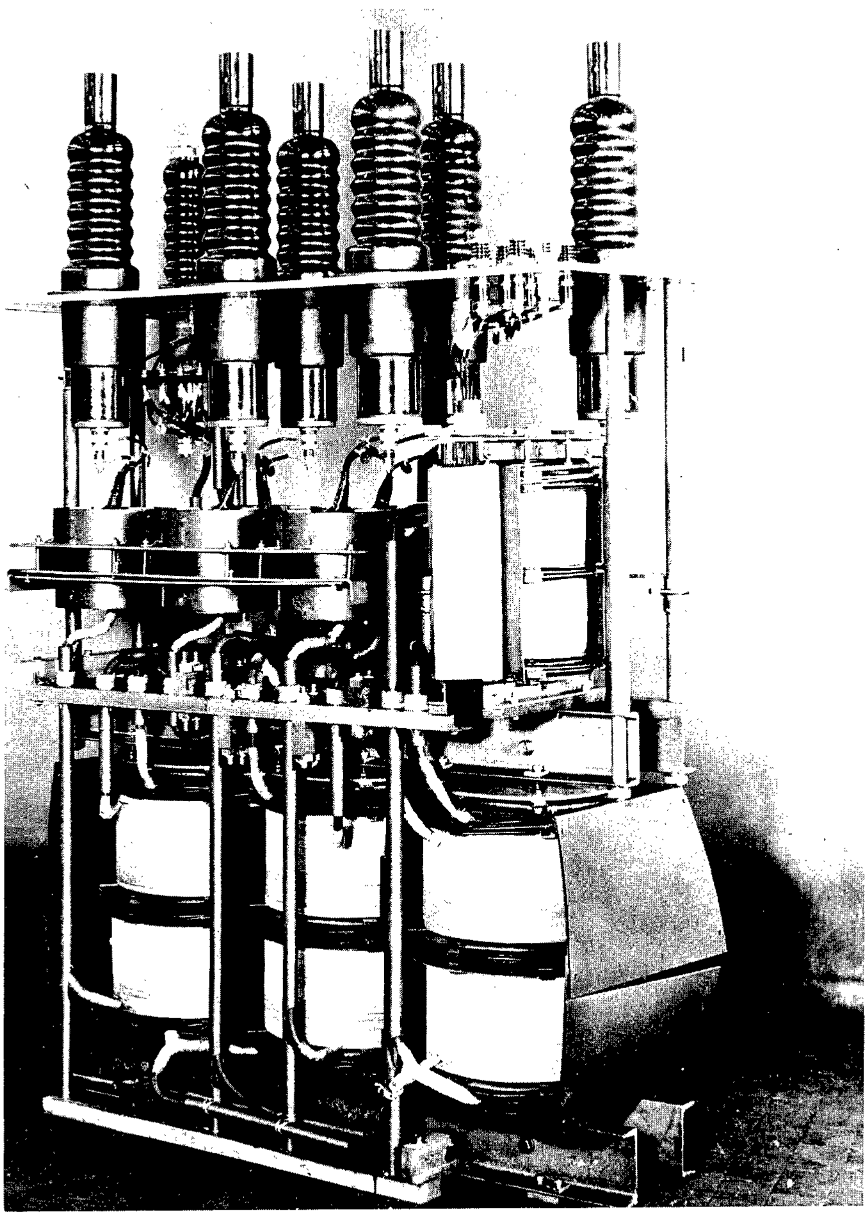


Fig. 2.29 —Beta decell-rectifier transformer unit, oblique view of high-voltage side with tank removed.

Chapter 3

REVISIONS IN RECTIFIER AND AUXILIARY EQUIPMENT

Any proposed change in the process equipment of the electromagnetic process was always evaluated by two primary criteria: How much would it affect production? How much time would be involved? The factors of effect on production and time were critical during the war when maximum production in minimum time was essential and when the shortage of skilled man power was acute. The electromagnetic process involved approximately 1,000 similar units operating simultaneously (384 in Alpha I, 480 in Alpha II, and 288 in Beta), and a minor plant-wide change could involve thousands of hours in labor and lost production. Consequently only those changes were made which could benefit production quickly, even though much of the equipment was known to be inadequate for maximum production, minimum maintenance, and/or ease of operation.

1. CHANGES IN RECTIFIER TUBES

The rectifier equipment as originally installed was supplied by the General Electric Company. The magnitude of the initial installation greatly overtaxed their tube-manufacturing facilities and necessitated the opening of a new plant to manufacture the GL-605 water-cooled tubes. After the start of operation, it became evident that the rate of failure of the KC-4 and GL-605 rectifier tubes was higher than the rate at which General Electric could replace them. It therefore became necessary to locate alternate sources of supply quickly in order that production would not be handicapped.

The alternate supplies and tubes used were (1) radiation cooled: Westinghouse, WL-616; Amperex, KC-4-A; Amperex, KC-4-3; Machlett, ML-100 and (2) water cooled: Federal, F-660; General Electric GL-562; General Electric, GL-697.

Later, as operation became more stable and as information was collected on the rates of failure of the various rectifier tubes, consider-

able work was done in an attempt to obtain tubes that would substantially increase operating efficiency and reduce maintenance, outage, and cost. In this connection several tubes, which had not been adopted for plant-wide operation, were either in development or being tested at the time the Alpha plant was shut down. These tubes are discussed in Chaps. 5 and 6.

2. REMOVAL OF SPARK GAP IN ALPHA I ACCELL RECTIFIER

The Alpha I accell rectifier as installed had a point-to-plane spark gap connected across its output. The theory of the gap was that its structure imposed a differential breakdown voltage so that it would not break down on normal forward operating voltage, but it could be broken by any spark in the mass spectrograph which caused reflected voltage of high magnitude or opposite polarity to exist on the high-voltage transmission line. This was a protection for the rectifier. During operation it was found that the gap was a continual source of trouble if its spacing was set close enough to give any protection, since with such spacing the normal operating voltage of the rectifier could also break the gap. This caused unnecessary outage and imposed unnecessary short-circuit loads on the rectifier without providing the necessary protection from high-voltage transients. It therefore became imperative that the gap be removed from the circuit.

3. ALPHA I ACCELL-RECTIFIER CURRENT-LIMITING RESISTORS

The current-limiting charge and discharge resistors originally installed in the Alpha I accell filter circuit, as described in Chap. 2, Sec. 1, had an inadequate wattage rating for the duty cycle imposed upon them. The physical construction of the high-voltage cubicle was such that these resistors were mounted on impregnated wooden boards that might be set afire by the overheating of the resistors. Owing to the forced-air cooling of the cubicles a fire at this point would cause a great deal of damage before it could be brought under control. Resistors rated at 2.0 amp were furnished by the General Electric Company as replacements, but, unfortunately, cubicle fires continued at approximately the same rate. Further investigation and observation disclosed that these resistors with a normal rating of 0.4 amp would become so hot that a red glow was visible on the resistors. These observations suggested that, although under steady-state conditions this was a d-c circuit, the possibility existed that, during sparking flurries originating in the mass spectrograph, reflected high-frequency components might be present that would tend to cause resonance in the tank circuit composed of the distributed capacitance

and inductance of these resistors. If such a condition were to exist, high currents that would explain the observed phenomena would be possible in this tank circuit. Additional experiments were conducted (Chap. 6) which indicated that better operation could be obtained by eliminating the discharge-current-limiting resistor and adding to the circuit a 25-ohm 4,000-watt line-terminating resistor. Material for this change had been purchased for installation at the time the Alpha I portion of the plant was shut down.

4. DECELL LINE-TERMINATING CAPACITORS IN ALPHA I AND BETA

The decell line-terminating capacitor in both the Alpha I and Beta equipment was a two-section three-bushing type, insulated from its case for 30 kv and rated at 25 kv d-c working voltage per section, 50 kv total. The series connection was utilized, but a bleeder resistor was not supplied to equalize the voltage stresses across each section. The case of the line-terminating capacitor was connected to the case of the rectifier-filter capacitor in order that both cases could be discharged by a common grounding switch for the protection of service personnel. As a result of this intercase connection, when a gas kick occurred in the limiter tube, the voltage rating of one section of the terminating capacitor would be exceeded. This condition was corrected by removing the double-section capacitor and installing a single-bushing type rated at 50-kv working voltage between the capacitor bushing and the grounded case. The connection between the capacitor cases was removed in order that the case of the terminating capacitor could be operated at ground potential. Although the failure rate of the three-bushing capacitors had been excessive, it was found that after the substitution of the single-bushing capacitor, as described above, the failure rate decreased to essentially zero.

5. REVISIONS IN THE RECTIFIER AUXILIARY EQUIPMENT

In addition to the changes discussed above, it was found necessary to make numerous changes in the auxiliary control equipment for both the accell and decell rectifiers. These changes will be discussed in detail in this section.

5.1 Alpha II Decell-rectifier Induction Voltage Regulator. As Alpha II production increased, the load on the decell rectifier approached the rated value of 2.0 amp. At load currents less than this rated value it was found that the air-cooled induction voltage regulator for the rectifier was operating at too high a temperature. It therefore became necessary to redesign the cooling-air duct to the

regulator so that more cooling air would be forced through the induction voltage regulators by the cubicle blower in order that the regulator could operate at a safe temperature.

5.2 High-voltage-recycler Circuit. It was found shortly after the start of operation that the high voltage was tripped off a great many times a day by protective overload relays, owing to the nature of the high-voltage load presented by the mass spectrograph. This condition necessitated close observation of the circuit by the operator in order that excessive loss of production time would not occur. As a result it was felt that it would be necessary to install an automatic reclosure mechanism known as a "recycler" circuit in each cubicle. Two types of recycler circuits were designed and installed, one in the Alpha I equipment and the second in the first of the Beta buildings. In later installations General Electric provided their own design in Alpha II and subsequent Beta buildings.

The recycler circuit as installed in Alpha I consisted of a d-c–operated slug-type time-delay relay, which through auxiliary relays closed the rectifier main contactor at a predetermined interval after this contactor had been opened by the overload relays owing to a fault. In order to protect the mass spectrograph from excessive currents in case the fault should persist, an induction-disk time-delay relay was used to integrate the amount of power delivered to the mass spectrograph. The induction-disk relay was so connected in the circuit that the disk was driven in a direction that would close the relay contacts while the slug relay was timing out after a fault and so that the induction disk would be driven in the opposite direction by its normal spring reset mechanism while power was applied to the rectifier transformer. When the contacts of the induction-disk relay closed, they in turn operated auxiliary relays, which locked out the recycler circuit. Thus the induction-disk relay integrated the number of reclosures and the duration of time between overloads before locking out the automatic reclosure circuit. In operation the integrator relay was adjusted so that a sustained fault would be locked out after approximately five reclosures of the main contactor.

The Beta recycler equipment consisted of two electronic timers and the necessary associate auxiliary relays. The circuit was so arranged that after the main rectifier contactor had been tripped by a fault, the first electronic timer would time out and then reclose the contactor by means of the auxiliary relays. The second electronic timer was also energized at the time the main contactor tripped and started to time out. This second time-delay relay was so adjusted that its timing intervals were longer than those of the first. The timing-out contacts of the second relay were so arranged in the circuit that if a second

fault occurred before it had timed out, an auxiliary circuit would be operated which would lock out the recycler. This required that the next reclosure of the high-voltage circuit be made under the manual supervision of the cubicle operator.

As has been stated previously, the Alpha II high-voltage cubicles were supplied with a recycler circuit designed and installed by the General Electric Company. However, it was found that these recyclers were not entirely satisfactory, the objection to this type of recycler circuit being that no provision was made in the circuit to prevent manual reclosure of the high-voltage contactor while the time-delay relay was timing out. In operation it was found that in many cases the operator would manually reclose the high-voltage circuit before the recycler time period had elapsed, thus imposing a rapid-duty cycle on the step-start resistors and contactors, causing excessive failure of this portion of the circuit. This condition was corrected by rewiring the recycler so that the manual control switch energized the recycler circuit in the same manner as the overload relays. This guaranteed that a 2-sec interval would elapse between reclosures of the high-voltage-rectifier contactor.

5.3 Changes in Step-start Equipment and Circuit. One of the greatest sources of trouble in the rectifier auxiliary equipment of the first Beta building and the Alpha I plant arose from failures in the step-start circuit. These failures were attributable to two factors: (1) the rating of the circuit components and (2) the fact that when a fault occurred in the operating unit the operators attempted to re-energize the rectifier as fast as possible until the fault had cleared. Attempts were made to correct this second condition by additional training of the operating personnel; however, this did not result in eliminating the failures in this circuit. This heavy-duty cycle on the contactors and resistors resulted in many cubicle fires caused by contactor phase-to-phase flashover and overheating of the resistors.

The step-start circuit for the accell and decell rectifiers was modified by paralleling the input circuit of the two rectifiers and energizing them through a single 150-amp contactor, which replaced the individual 75- and 25-amp contactors in the initial installation. The auxiliary 25- and 15-amp contactors, which initially energized the two sets of step-start resistors, were replaced by a single 75-amp contactor and the 2- and 6-ohm 180-watt resistors. After the two step-start circuits had been combined into a single circuit using equipment with a higher rating, failures in this portion of the circuit became infrequent.

At the same time that the above change was made, the control circuit to the auxiliary contactor was rearranged so that the coil of this

contactor would be deenergized when the main contactor closed. This change ensured that the main contactor would at all times carry the full-load current and that none of this current would be shunted through the auxiliary contactor and the step-start resistors under normal operating conditions. In the Alpha II equipment, this required auxiliary control contacts to be mounted on the main contactor frame. It was also found necessary to change the spring on the auxiliary contacts to prevent bouncing, which had caused excessive burning of these contacts.

5.4 Changes in Overload Relays and Auxiliary Circuits. The d-c overload relay used in the decell-rectifier circuit of Alpha I and Beta was a double-pole double-throw 230-volt relay using a 28-volt d-c coil. The relay coil was shunted by a 15-ohm variable resistor connected in series with the ground side of the d-c rectifier.

During operation it was found that this relay circuit was not satisfactory because the relay coils were continually burning out owing to arc-overs. Tests were made to determine the reason for this type of failure, and voltage in the range of 5 kv across the coil was observed under transient conditions. Owing to these failures and to the fact that experience had shown that this relay would not furnish protection for the rectifier, the relays were removed from the circuit.

Much trouble was experienced with the overload relays in the primary circuits of the two rectifiers because of excessive burning of the contacts of these relays. Investigation of the protective circuit disclosed that the overload relays were so connected that it was necessary for the contacts to break the coil current of the auxiliary contactor in the tripping circuit and that the contacts of these relays were not adequate for this type of service. As a result it was necessary to rewire this circuit so that auxiliary contacts would break the tripping circuit, the overload contacts being used only to energize this circuit.

The overload relays initially installed in the high-voltage cubicle were the General Electric IAC induction-disk time-delay type. These relays were designed for use with power equipment in which they would be required to operate at a maximum of no more than once per month, but in the application at this plant they were called upon to operate an average of 100 times per day and in rare cases possibly as many as 1,000 times per day. Under this type of service it was found that the very delicate relay contacts would burn badly and that the contact heads on the instantaneous plunger would break. Since it was impractical to procure and install an adequate relay in the existing equipment, it became necessary to modify the relays by supplying

heavier contact disks, stronger contacts, and stronger contactor heads in order to reduce the maintenance time as much as possible.

Because the IAC relays required so much maintenance and because their location in the high-voltage cubicle made it difficult to service them in place and practically impossible to remove, it was felt that the best solution to this problem was to convert these relays to the draw-out type. Cost studies indicated that it would be too expensive to convert these relays by using standard conversion parts, and hence an alternate scheme was devised by CEW-TEC, and the relays were converted by this modification. The modification consisted in replacing the studs on the rear of the relay with a brass single-pole plug and mounting telephone-type single-pole jacks, insulated by fiber washers, in a steel panel to support the relay. Since the relays were located inside the high-voltage cubicle it was necessary that the equipment be deenergized before access to the relay position could be gained. This eliminated the necessity for a relay jack, which would short out the current transformer. This modification of the IAC relay to a draw-out type proved to be relatively inexpensive and satisfactory and reduced relay maintenance.

5.5 Beta Decell Load-current Meter. The current from the Beta decell rectifier was measured by a d-c ammeter mounted on the front door of the high-voltage cubicle and connected in the ground circuit of this rectifier. This meter exploded numerous times, endangering the operators in front of the cubicle. Investigation of the circuit disclosed that the protective choke for this meter was located on the ground side of the meter and that a long lead extended from the door for a considerable distance inside the cubicle before being connected to the cubicle ground bus. This length of lead offered sufficient surge impedance to transient currents to cause the potential of the meter to rise high enough above ground to break down the insulation. This type of meter failure was eliminated by moving the protective choke to the ungrounded side of the meter and by grounding the meter directly to the cubicle door, thus eliminating surge impedance in the ground lead.

5.6 Filament Induction-regulator Control. The original Beta equipment was supplied with individual controls in the rectifier, regulator, and limiter filament circuits. In order to save time in energizing these control circuits, they were rewired to provide automatic operation. This was accomplished by interlocking the control relays with the limit switch, which operated to raise the induction voltage regulator to its operating position after it had automatically run down to the lower limit. The change eliminated the necessity of manual control of these three circuits.

5.7 Filament Meter Selector Switch. The Beta equipment as supplied was provided with individual meters for the rectifier, regulator, and limiter-tube filament circuits. Since metering of these circuits was seldom required and since the panel space occupied by these meters was needed for auxiliary monitor meters, which will be discussed later, a single meter with selector-switch arrangement was substituted in place of the three original meters.

Chapter 4

EQUIPMENT RATINGS AND OPERATING REQUIREMENTS

Plant operation was started with all rectifiers operating at voltages and currents below their name-plate ratings. The demand for increased production, however, soon necessitated an increase above these ratings. Table 4.1 gives the name-plate ratings of the six rectifiers as compared with the actual operating currents and voltages used in plant operation.

In general each of these rectifiers was operated at the maximum output voltage that could be obtained with its induction voltage regulator set for the upper-limit value. In decell rectifiers the characteristics of the electronic regulator for a particular value of load current determined the upper voltage limit. This is discussed in detail and regulation curves for the rectifier are given in Chap. 9, Sec. 1.2. It should also be borne in mind that during sparking flurries these rectifiers were called upon to deliver short-circuit currents that were 150 per cent of the nominal operating current for a period of approximately 2 sec before the rectifiers were cleared from the line by the overload protective relays. Owing to secondary phase-to-phase arc-overs, short-circuit currents of the order of ten times the rated current value existed for periods of from six to ten cycles before the instantaneous relays could clear the transformer.

It will be noted from Table 4.1 that the Alpha I accell rectifier was the only one of the three accell rectifiers that was operated above its name-plate rating. This rectifier was operated at approximately 50 per cent of its rated current value and at 127 per cent of rated voltage.

In Alpha II and Beta the accell rectifiers were operated at normal voltage and at approximately 50 per cent of current rating. Even though the Alpha I rectifier was operated at a voltage that was higher than its nominal value, no apparent damage resulted, and in all cases the temperature rise of the transformers was within the safe operating value.

The decell rectifiers were always operated at a voltage higher than their name-plate rating, and in Alpha II they were operated at a current value higher than the manufacturer's rating. The Alpha I decell rectifier was operated at 100 per cent of its current rating and 109 per cent of its rated voltage, and the Alpha II decell rectifier was operated at 110 per cent of its rated current and 110 per cent of its rated voltage. The Beta decell rectifier was operated at only 65 per cent of its rated current but was operated at 112 per cent of its normal voltage.

1. TRANSFORMER LOAD AND RATING

In the discussion above it was pointed out that some of the rectifiers used in the equipment at this plant were operated at d-c loads higher than their name-plate rating. This, however, does not mean that the transformers associated with these rectifiers were overloaded. The manufacturer had provided a sufficient safety factor so that under conditions of actual operation the decell rectifier in the Alpha II equipment was the only one that was operated at higher than the transformer name-plate rating. The Alpha II decell transformer was rated at 2.0 amp and was actually operated under steady-state conditions at 2.2 amp.

It should be emphasized again that the steady-state condition cannot be used as a criteria for the operation of this equipment because the nature of the load imposed severe transients on both the rectifier transformer and the rectifier tubes. Such transients were initiated by arc-backs in the rectifier itself and by sparks that occurred in the load. In the Alpha I equipment, for example, it was found that voltages in the range around 150 kv existed between the end point of the interphase transformer and the high-voltage bushing of the rectifier transformer. This rectifier transformer frequently flashed over from bushing to bushing and from the transformer bushings to the side wall of the high-voltage cubicle.

It has been suggested that actually the bushings were acting as protective gaps allowing high-voltage transient sparks to take place in air rather than through the transformer oil, thus giving a certain degree of protection to the transformer.

2. RECTIFIER TUBES

In order to analyze rectifier-tube service conditions it is necessary to divide plant operation into three major sections, namely, Alpha I, Alpha II, and Beta, and then consider the accell and decell rectifiers used in each of these processes. Service conditions can readily be

determined by comparing the tube ratings with the actual operating values. To facilitate this comparison, Table 4.2 has been compiled. Ratings of the tubes adopted for plant operation and service conditions for normal operation of the accell and decell rectifiers in the Alpha and Beta processes are shown.

From this table the following two conclusions can be drawn:

1. For rated filament voltage, normal operating conditions were well within the tube ratings.

2. Service conditions for the air-cooled rectifier tubes were more severe in the decell rectifier of the Alpha I process than in any other plant application. It is important to note, however, that these data do not take into account operation during abnormal rectifier conditions.

It is also pointed out that in the accell rectifier used in Alpha I it was not possible to operate satisfactorily with the rectifier tubes operating with normal emission. It was found necessary to operate these rectifiers under emission-limiting conditions in order that the overload relays would not be tripped by every transient caused by arcing at the load. It was found that, by operating this rectifier emission-limited, load sparks in many cases would extinguish before the protective relays operated. Operating under these conditions and under faulty load conditions, the tube plate-dissipation rating was at times exceeded by more than 200 per cent. Although this was not desirable from the viewpoint of tube life, it was tolerated in order that over-all production would be increased.

3. INDUCTION VOLTAGE REGULATORS

The induction voltage regulators associated with accell and decell rectifiers were operated at their normal rated voltage. The only one of these regulators that was overloaded was the one used in the primary circuit of the Alpha II decell rectifier. This induction voltage regulator carried approximately 105 per cent of its normal current rating.

4. CAPACITORS AND RESISTORS

Under steady-state conditions the filter and terminating capacitors and their associate resistors were operated within their d-c rating. However, surges that in general tended to overload the resistors in the filter circuit were reflected, owing to sparking at the load. No accurate measurements were made as to the degree of overload that existed during sparking flurries. Observation of these resistors under this condition, however, seemed to indicate that they were overloaded to approximately 500 per cent of their d-c rating. The degree of over-

load was dependent on the type of sparking flurries that existed, these flurries being of different magnitude and duration for each of the classes of service.

Measurements indicated that the reflected voltages generated by sparking flurries were not in excess of the rated d-c value for the capacitors used in this equipment. The only overvoltage condition that existed on the capacitors was due to the type of filter connection used in the Alpha I and Beta equipment, in which the voltage existing across the limiter tube during sparking flurries was applied between one terminal of the filter condenser and the condenser case. These were two-section condensers, and the insulation between the individual sections and the case was not ample to withstand this voltage. This has been discussed in Chap. 3, Sec. 4, and will be further discussed in Chap. 5, Sec. 3.

5. CONTACTORS AND STEP-START RESISTORS

The contactors and step-start resistors provided in this equipment were of adequate rating, provided that a steady-state load existed. Unfortunately, a steady-state load did not exist. Owing to the nature of the load and the sparks that resulted in this load, these contactors and resistors were called upon to operate an average of 100 times a day, and in many cases this rate increased to 1,000 operations a day. Because of this heavy-duty cycle excessive heating in the step-start resistors resulted. This condition became so bad in the case of Alpha I and the original Beta building that it was necessary to change to higher-rated resistors. In the rest of the plant this overheating of resistors was not so excessive and was therefore tolerated during plant operation.

Because the contactor holding coils were energized from the same 460-volt bus as the rectifier transformers and because the protective relays were inadequate, good relay coordination could not be established between power contactor and the channel-supply air circuit breaker. Therefore in many cases the contactor would attempt to clear a fault current before the air circuit breaker could operate. Since these fault currents were around 20,000 amp, which was greatly in excess of the contactor interrupting capacity, such an operation usually destroyed the contactor.

6. RELAYS

The protective relay equipment supplied with these rectifiers was inadequate for this type of service. The protective relays, which were of the General Electric IAC type, were provided with instantaneous overload attachments, these relays being normally designed to work

in a circuit where overloads and faults were infrequent. However, in this equipment, as has been pointed out, these relays were called upon to operate hundreds of times per day. Owing to the heavy service imposed upon these relays, it was found impossible to maintain accurate relay settings to provide coordination between these relays and the channel air circuit breakers. Because these relays were inadequate for this service, certain changes that have been described in Chap. 3, Sec. 5.2, were required. The service record of these relays will be discussed in Chap. 5, Sec. 3.

Table 4.1—Rectifier Ratings Compared with Operating Loads

	Name-plate rating		Operating load	
Rectifier	Voltage, kv	Current, amp	Voltage, kv	Current, amp
Alpha I accell	15	0.4	19	0.2
Alpha II accell	35	1.0	35	0.55
Beta accell	40	0.4	40	0.2
Alpha I decell	35	1.0	38	1.0
Alpha II decell	35	2.0	38.5	2.2
Beta decell	35	1.0	38	0.65

Table 4.2—Comparison of Tube Ratings and Service Conditions*

	Tube ratings							Service conditions			
Tube	Filament voltage, volts	Filament current, amp	Peak plate current, amp	Average plate current, amp	Average plate dissipation, kw	Peak inverse voltage, kv	Rectifier service	Peak plate current, amp	Average plate current, amp	Average plate dissipation, kw	Peak inverse voltage, kv
General Electric KC-4	20.0	24.5	1.0	0.45	0.75	150	Alpha I accell	0.14	0.08	0.04†	35
							Alpha II accell	0.225	0.145	0.09	75
							Beta accell	0.14	0.08	0.03	80
Westinghouse WL-616	20.0	24.5	1.0	0.25	0.6	150	Alpha I decell	0.40	0.23	0.22	100
							Beta decell	0.275	0.16	0.10	100
Machlett ML-100	20.0	24.5	1.0	0.55		150	Alpha II accell	0.225	0.145	0.04	75
							Beta accell	0.14	0.08	0.009	80
							Alpha I decell	0.40	0.23	0.06	100
							Beta decell	0.275	0.16	0.04	100
Amperex KC4-A and KC4-3	20.0	24.5	1.0	0.45	0.75	150	Alpha I accell	0.14	0.08	0.04	35
General Electric GL-605 and 562, and Federal F-562	22.0	52	7.5	2.0	20	50	Alpha II decell	1.95	1.12	1.8	45
Federal F-660	22.0	52	7.5	2.0	40	50	Alpha II decell	1.95	1.12	1.8	45

*These data are the average conditions for the period January to July 1945 and do not include abnormal occurrences such as rectifier shorts. The average plate dissipation was calculated by multiplying the operating current by the corresponding tube drop at rated filament voltage.

†Tube filament voltage set so that tubes will emission-limit when rectifier shorts occur, thereby decreasing the number of relay operations.

Chapter 5

SERVICE RECORD

The CEW-TEC plant was operated on a three-shift basis seven days a week with all the high-voltage supplies operating at all times possible. Operation was broken up into runs having an average life of approximately two weeks in Alpha I and Alpha II, but in Beta, owing to the nature of the charge, runs averaged only approximately two days. Termination of these runs was staggered to reduce the amount of required maintenance equipment and personnel. In Alpha I and Alpha II the average required time between runs for equipment servicing and pumpdown was approximately 10 hr. Because of the smaller size of the equipment in Beta, this interval time was reduced to approximately 1½ hr. Under these conditions the high-voltage supplies were operated on an average of approximately 23½ hr per day, this being 98 per cent of the total time available.

In order that equipment failures might be analyzed and in order that the amount of maintenance time required to repair such failures might be evaluated, a system of trouble tickets was initiated for the electrical-maintenance personnel in the operating buildings. By analyzing these trouble tickets it was possible to evaluate the relative merits and obvious defects of the operating equipment. A summary of the data supplied by these trouble tickets for a typical period is shown in Tables 5.1 to 5.3. After initial start-up troubles were eliminated, it was found that in Alpha I there were approximately 1,200 difficulties per month reported for the 384 voltage supplies in operation. Alpha II reported approximately 400 difficulties per month for 384 supplies, and Beta reported 800 per month for 288 supplies in operation.

In the following sections detailed discussions of the troubles developing in each major portion of the high-voltage supplies will be given.

1. TRANSFORMERS

In general, very few failures that could be attributed to transformer failures occurred in any of the high-voltage supplies. During the first

18 months of plant operation, Alpha I had only eight high-voltage transformer failures, Alpha II had only one failure, and Beta had only three failures.

The failure of six of the Alpha I decell transformers could be attributed to the following causes: (1) one high-voltage winding was shorted to ground, (2) one interphase-transformer winding was shorted to ground, (3) one high-voltage winding had an intermittent fault, the cause of which was assumed to be overheating, (4) one filament-transformer winding was shorted, (5) one filament transformer had an intermittent fault, the cause of which was not determined, and (6) one transformer, although it did not actually fail, was a persistent troublemaker because of bushing flashover and tube failure.

In the Alpha I decell transformers a potential hazard existed owing to poor inspection during the manufacture of the transformers. It was known that approximately 60 out of 384 decell transformers in operation had interphase transformers in which the winding connections were not soldered. There was no way to identify these transformers without removing them from the transformer tank. As a result this condition was allowed to exist during plant operation and was to be remedied at the time of transformer failure. However, none of the transformers in which this condition existed failed during plant operation.

The transformer that was a persistent troublemaker was returned to the factory for test, but no satisfactory reports were received as to the defects that had caused the abnormal bushing flashover and tube failure during plant operation. As has previously been mentioned in this volume, decell rectifier transformers were subject to frequent bushing-to-bushing flashovers. It was found that these flashovers occurred at an average rate of approximately two per day per transformer.

The failure of the two Alpha I accell rectifier transformers during plant operation was assumed to be due to overheating.

The Alpha II decell rectifiers were operated actually at a slight current overload; however, only one of these transformers failed during plant operation. Investigation of this transformer disclosed that this fault was due to failure of the insulation between a high-voltage winding and the case.

Although very little trouble was experienced with the high-voltage transformers in the Beta equipment, it was found in initial start-up that a number of the decell transformers had the leads from the center of the interphase winding to the interphase bushing broken. This condition was corrected, and no other failures of this type were experienced. Three decell transformers failed during the first 18 months

of operation owing to (1) an insulation breakdown between the high-voltage winding and ground, (2) an open circuit in the high-voltage winding, and (3) flashover of the high-voltage section, an intermittent fault of undetermined origin.

2. RECTIFIER TUBES

In this section the discussion is arranged to consider, first, the radiation-cooled rectifier tubes used and, second, the water-cooled types used. Several companies supplied rectifier tubes to CEW-TEC. For each class the failures of the original type, design changes that were made, and failures of the improved types will be discussed.

An over-all picture of the tube development that was carried out during plant operation is presented in Figs. 5.1 and 5.2. Figure 5.1 shows the development of high-voltage air-cooled rectifier tubes, and Fig. 5.2 shows the development of high-voltage water-cooled rectifier and limiter tubes.

Rectifier tubes were a major maintenance problem during plant operation. The magnitude of this problem can be appreciated more readily from Table 5.4.

Tables 5.5 to 5.7 show the itemized tube costs for the three processes. Costs are based on the average life found for the original type supplied with the General Electric equipment as compared to the improved types developed during plant operation. Taking into consideration the differences in the cost of tube replacements, as well as the amount of time lost in production in replacing the number of tubes listed above, it will be seen that a great deal of development time and money could justifably be spent in developing a satisfactory tube for this class of rectifier service.

To determine the life expectancy of a tube in a given class of service, a representative sample of tubes in this particular service has been selected and a survival curve for this group has been plotted.

2.1 Radiation-cooled Rectifier Tubes. In the following discussion of air-cooled rectifier tubes, analysis centers in general on the decell rectifier of the Alpha I process. As CEW-TEC gained experience, based on plant operation, it was indicated that, if an air-cooled rectifier tube could be designed to withstand the decell service in Alpha I, it would readily withstand decell-rectifier service in Beta or the accell-rectifier service in any of the three processes.

(a) General Electric Tubes. All the tubes in the initial installation were the KC-4 type furnished by the General Electric Company. The life expectancy of this tube in Alpha I decell-rectifier service has been found to be approximately 2,900 hr, as shown by the KC-4 survival curve, Fig. 5.3.

Analysis of tube failures for the period of KC-4 operation in Alpha I decell-rectifier service shows the following:

Classification of tube defects	Per cent of group
Burned-out filament section wherein filament structure had been badly distorted and shorted to the spiral support	35
Burned-out filament caused by either inverse emission or evaporation. Experience indicated that most of these failures were due to inverse emission	28
Gassy tubes (includes those which were leakers and those which were gassy by test specifications)	25
Burned-out filament leads (external to vacuum) wherein there was no visible fault in the physical circuit	10
Miscellaneous	2

These data show that the life of the KC-4 tube was not limited by filament evaporation, as would be expected in the case of a properly designed tube, but was limited by inherent tube weaknesses (filament bowing and inverse emission) and results of faulty manufacturing techniques (gas and filament-lead burnout).

The data presented above cover the entire period of operation during which KC-4 tubes were used in the Alpha I service. It would, however, be well to refer to KC-4 failure data collected in the early life of Alpha I. These data are important since the failures experienced early in operation caused CEW-TEC to initiate a development program to secure a more suitable tube. The failure data collected during the first few months of operation indicated the following:

Classification of tube defects	Per cent of group
Burned-out filament section wherein the filament structure had been distorted and shorted to the spiral support	52
Burned-out filament leads external to vacuum	22
Burned-out filament caused by inverse emission	16
Miscellaneous, principally gas	10

The above data indicated that over 50 per cent of the failures experienced in plant operation were due to a structural weakness in the filament, allowing it to bow. When this was pointed out to the General Electric Company, it was suggested that the filaments be operated at a lower temperature, thus reducing distortion. Therefore the KC-4 filament voltage was lowered as far as was practical without reducing the required emission, the value actually being of the order of 18.0 to 19.0 volts, depending on the actual emission required. This resulted in a decrease in the percentage of failures due to filament bowing, as can be seen by comparing the two sets of data given above. It should be noted, however, that although the number of tube failures due to filament bowing was decreased, the number of failures due to inverse emission was increased. An inspection of the above data indicates that the sum of the percentages of filament-bowing and inverse-emission failures for filaments operating at 20 volts was 68 per cent, but after the voltage had been dropped to below 20 volts, this sum fell to only 63 per cent. It was concluded therefore that reducing the filament voltage was not the solution to the high rate of failures caused by poor mechanical construction of the KC-4 filament.

The high percentage (22 per cent) of burned-out filament leads was attributed to manufacturing techniques, and this was pointed out to the General Electric Company. The company took steps to change its manufacturing techniques, and this type of failure decreased to only 10 per cent. The increase in gassy-tube failures from 10 per cent for the first few months of operation to 25 per cent during the total of plant operation can be attributed to several factors, such as improper outgassing, shelf life, and slow leakers, i.e., tubes that had minute leaks causing them to become gassy after an extended period of operation.

Consequently a program was initiated at the General Electric Company to modify the KC-4. This program aimed to eliminate such failures as filament bowing and inverse emission and at the same time to minimize tube gas content. The first of a series of modified tubes was known as the "ZP-624," a low-drop type. Filament voltage, plate dissipation, and inverse-voltage rating were the same as for the standard KC-4. This tube had a filament structure of the same general type as that in the KC-4 (Fig. 5.4) but differing in that the filament wire was of greater diameter with a larger filament-helix diameter. The ZP-624 used side-support rods instead of the spiral support used in the KC-4. It was the belief of General Electric that the operating temperature of the anode and filament would be reduced by this type of construction, thereby tending to eliminate filament bowing and inverse emission.

To test this design, General Electric delivered 24 tubes to CEW-TEC in April 1944, 18 of which were tested in Alpha I decell-rectifier service. These tubes were installed in two groups of six each with the remaining six tubes being used as spares. The filaments were operated at 19.0 volts. The average life of the tubes was found to be 700 hr. The results of this test were as follows:

Classification of tube defects	No. of tubes	Per cent of group
Bowed filament structure, filament shorted to plate	12	67
Inverse emission	2	11
Miscellaneous (no record of tube failure)	4	22

From this data it was obvious that the design changes incorporated in the ZP-624 had not eliminated the main defects of the KC-4, namely, filament bowing.

General Electric next modified the design of a standard KC-4 tube by using a molybdenum anode 0.020 in. thick rather than the conventional 0.012 in. It was the opinion of General Electric that this type of anode would make possible greater thermal conductivity and reduce localized heating, thereby tending to reduce failures due to filament bowing and inverse emission.

Thirty tubes built according to this design were received by CEW-TEC in December 1944. This entire group was installed in groups of six in Alpha I decell rectifiers. The filaments were operated at approximately 18.5 volts. The average life of the tubes was found to be approximately 4,000 hr. The results of this test were as follows:

Classification of tube defects	No. of tubes	Per cent of group
Bowed filament structure	11	37
Gas leakers and tubes gassy by test specifications	5	17
Tubes still in operation at the time Alpha I plant was shut down	7	23
Tubes removed from Alpha I and placed in other process rectifier service	3	10
Miscellaneous (tubes removed from service, no record of failures)	4	13

The above data definitely indicated that the heavy-wall anode did tend to increase tube life and reduce filament failures due to bowing and inverse emission. It should also be noted that no tube in this group failed because of inverse emission.

In January 1945, shortly after the start of the test of the heavy-wall-anode tubes described above, CEW-TEC received six tubes from General Electric for special test in Alpha I decell rectifiers. These tubes were of the standard KC-4 design but had a tantalum ring at the lower section of the anode, the purpose of which was to increase the thermal capacity of the anode. These tubes were put into operation with their filaments operating at approximately 18.5 volts. The findings of this test were as follows: (1) average life of tube was 2,400 hr; (2) all six tubes failed owing to inverse emission. Although these data are very limited, they would appear to indicate that this design did not reduce failures due to inverse emission.

In January 1946 General Electric delivered 30 additional tubes to CEW-TEC. These were to be used in a test to determine whether or not the placing of getter material in the evacuated tube envelope of a standard KC-4 would reduce tube gas condition. This getter was expected to absorb any gas that might be evolved from the tube element or envelope owing to heating during operation. These tubes were submitted to an initial inspection test, and 18 tubes were rejected because of gas or broken elements, the majority being rejected because of gas. The remaining 12 tubes were placed in operation in groups of six in Alpha I decell rectifiers. The filaments were operated at approximately 18.5 volts. The average life of the tube was found to be 850 hr. The results of this test were as follows:

Classification of tube defects	No. of tubes	Per cent of group
Filament failures due to filament bowing and inverse emission	7	58
Gas leakers or gassy by test specifications	2	17
Miscellaneous (tubes removed from service, no record of failures)	3	25

The number of tubes tested was too small to serve as a basis for drawing a final conclusion as to whether or not the idea of using a getter in a KC-4 tube was of any value. However, experience with

tubes produced by other manufacturers indicates that a getter is not necessary in a tube that has been properly processed before sealing, and it seems therefore that this idea had little value.

Summarizing the attempts at modifying the KC-4 tube, it appears that design progress was made only in the tube of the heavy-wall anode, which tended to reduce inverse-emission failures and to minimize the effect on tube life attributable to the inherent weakness of the filament structure, which allowed the filament to bow under operating conditions. Consequently General Electric agreed to redesign this type of rectifier tube completely. A new design seemed to be the only solution to the problem of developing a tube adequate for Alpha I decell-rectifier service. The result of this decision was the development of two experimental tubes designated as "ZP-680" and "ZP-681." After samples of the ZP-680 and the ZP-681 had been delivered to CEW-TEC, General Electric concluded that, owing to difficulties in manufacturing the ZP-680, they wished to discontinue any further work or discussion on this tube and to continue to develop only the ZP-681.

Work was continued on the ZP-681, and the tubes finally delivered to CEW-TEC were known as "GL-681," Fig. 5.5. These tubes had the characteristics and ratings indicated in Table 5.8.

The first of 12 experimental tubes of the ZP-681 type received by CEW-TEC were tubes having a 22-volt filament and a 0.006-in. anode made of tantalum. Six of these tubes were installed in one Alpha I decell rectifier, and the remaining six were held as spares. The tubes could not be operated at rated filament voltage without overloading the filament transformers. The test was made at a filament voltage of 20 volts, the maximum output of the filament transformers. The results of this test were that nine tubes failed in the first 100 hr of operation from inverse emission. The test was then discontinued.

When advised of the outcome of this test General Electric concluded that the relatively light anodes used in these experimental tubes did not have sufficient thermal capacity to minimize or prevent inverse-emission failures.

In order to increase the anode thermal capacity of the ZP-681 tubes and reduce failures due to inverse emission, General Electric changed the anode to one made of 0.020-in. molybdenum with 0.006-in. tantalum end bands. Twelve of these experimental tubes were tested for inverse-voltage characteristics by standard test procedure and were installed in an Alpha I decell rectifier that was operating with an average load current of approximately 700 ma. The filaments were operated at 22 volts by overloading the filament transformers. The results of this test were as follows:

Tubes were installed May 1, 1945. No failure had occurred up to the time of the Alpha I shutdown. This amounted to approximately 3,000 hr of operation.

This design appeared to be quite successful, but because a tube with a 22-volt filament was not practical for plant-wide operation owing to the fact that it would overload the filament transformers, General Electric redesigned the ZP-681 filament for 20-volt operation. The design of the anode structure remained the same as the design used in the first heavy-anode tube, i.e., 0.020-in. molybdenum plate with 0.006-in. tantalum end band. Six of these tubes were placed in service in an Alpha I decell rectifier at CEW-TEC with their filaments operated at 20.0 volts. The results of this test were as follows:

The tubes were installed Aug. 1, 1945. No tube failure had occurred up to the time of the Alpha I shutdown. This amounted to only approximately 1,000 hr of operation.

Owing to the fact that only six tubes were tested and that these had been tested only for a period of approximately 1,000 hr, no conclusion was drawn as to the value of this new design. It was then decided to continue testing these tubes in the decell rectifier of a Beta cubicle. Six tubes were installed with their filaments operating at 18.0 volts. After approximately 1,200 hr of operation without a tube failure, 108 additional tubes of this type were installed. The filaments of these tubes were also operated at 18.0 volts. These tubes, namely, the ZP-681, were installed between Jan. 10 to 15, 1946, and had completed seven months of operation in July 1946, during which period 17 failures had occurred. The survival curve (Fig. 5.6) for this seven-month period indicated a life expectancy of 7,000 hr. The survival curve for the ZP-681 follows very closely the curve for initial installation of fresh KC-4 tubes (Fig. 5.7) in the first 216 Beta cubicles. A comparision of the survival curve for the ZP-681 and for the initial installation of KC-4 tubes indicated that the ZP-681 was not an appreciably better tube than the KC-4 under identical operation conditions. At initial installation the KC-4 tubes showed a life expectancy of 7,000 hr which was identical with the life expectancy indicated for the ZP-681 tubes at initial installation. The survival curve for replacement of KC-4's from old stock, however, showed a life expectancy of only 3,500 hr. At the time of writing it remains to be seen whether or not the ZP-681 will show a similar reduction in life expectancy as the replacement stock ages.

(b) Westinghouse Tubes. As has been mentioned previously, all the original air-cooled rectifier tubes were supplied by General Electric. However, it was felt that an additional source of supply was necessary. Therefore Westinghouse was asked to submit an air-cooled rectifier

tube that would be the mechanical and electrical equivalent of the General Electric KC-4. The tube that was submitted by Westinghouse for CEW-TEC approval was known as the "WL-616." Physically the structure of this tube was almost identical with the structure of the KC-4, as will be noted from the group photograph of air-cooled tubes, Fig. 5.8. Electrical characteristics as given by Westinghouse were similar to those of the General Electric KC-4.

In order that experience with the WL-616 under actual operating conditions might be obtained, 34 cubicles in Alpha I were equipped with these tubes in both the accell and decell rectifiers. These installations were made over the period May 6 to 23, 1944. In the following discussion only the operation of these tubes in decell-rectifier service will be considered. When these tubes were first installed, they were operated at rated filament voltage of 20.0 volts. It was soon noted, however, that this filament structure had weaknesses similar to those of the KC-4, i.e., bowing of the filament and shorting of the filament to the spiral support. As a result the filament voltage was reduced from 20.0 volts to a value between 18.2 and 19.2 volts, depending on the available tube emission as determined by test. This procedure was adopted as a result of experience gained in the operation of the KC-4 types as discussed above.

On the basis of this test and subsequent use of WL-616 throughout the Alpha I plant it was determined that the average life expectancy for the WL-616 in Alpha I decell-rectifier service was approximately 2,400 hr. The WL-616 survival curve is shown in Fig. 5.3.

Analysis of tube failures for the period during which WL-616 tubes were in operation in Alpha I decell-rectifier service shows the following:

Classification of tube defects	Per cent of group
Burned-out filament section wherein the filament structure had been badly distorted and shorted to the spiral support	39
Gassy tubes, including those which were leakers as determined by tube tests	35
Burned out filaments, due to either inverse emission or evaporation (from experience it is reasonable to expect that most of these failures were due to inverse emission)	23
Miscellaneous (broken envelopes, broken elements, etc.)	3

The above data indicated that the life of the WL-616 was not limited by filament evaporation but was limited by inherent tube weaknesses (filament bowing and inverse emission) and results of faulty manufacturing techniques (gas). A comparision of the WL-616 defects, given above, with the defects of the KC-4 showed them to be the same, as would be expected in view of the fact that the designs of these tubes were identical and that both tubes had the same inherent weaknesses.

In order to overcome the inherent weaknesses of the WL-616 design, Westinghouse developed a new tube known as the "WX-3248." This tube had the same physical dimensions and rating as the WL-616. The experimental WX-3248 differed from the WL-616 in that it employed four straight elements in the filament structure rather than a spiral as in the older tube. Westinghouse delivered 24 of these experimental tubes to CEW-TEC in July 1944. Twelve of these tubes were installed in Alpha I decell rectifiers, and three of the tubes were installed in an Alpha I accell rectifier. When the remaining stock of spare tubes had been depleted, the WX-3248 tubes were removed from the accell rectifier and used as replacements in the decell rectifiers.

These tubes were operated at approximately 17.0 volts on the filament. The average life of the tubes was 200 hr. Test results were as follows:

Classification of tube defects	Per cent of group
Filament structure: in most cases the filament was found open at the center of one strand and showed no sign of melting, apparently having been broken by electrostatic stress; 12 tubes failed because of open filaments	50
Cathode seal press: all gassy conditions appeared to be due to a cracked cathode seal press; 9 of the tubes were gassy	37.5
Miscellaneous: mechanical breaks in filament circuit; 4 tubes had this defect	12.5

The excessive rate of failure of the WX-3248 design seemed to be due mainly to two structural weaknesses: filament structure and cathode seal press. Because of the structural weaknesses of these tubes and the fact that a tube with a higher emission rating was desired, further testing of this tube was discouraged.

In order to meet specifications for a tube with a higher current and inverse-voltage rating, Westinghouse next designed the WX-3260, later known as the "WL-619." Ratings of these WL-619 tubes were as follows:

Filament:	
Voltage, volts	20.0
Current, amp	32.0
Maximum rating:	
Peak plate current, amp	2.5
Average plate current, amp	0.75
Peak inverse voltage, kv	200
Average plate dissipation, kw	1.0

Fourteen WX-3260 tubes were received from Westinghouse in February 1945. Inspection of their design revealed that the tube would not withstand the electrostatic stress that would occur in plant operation; thus this tube could not be operated satisfactorily in a production cubicle until the design had been modified. The WX-3260 with a new filament design was resubmitted for test in July 1945. The filament construction of this tube is shown in the photograph of WL-619 filament structure, Fig. 5.9. The tubes were initially tested at 200 kv inverse no-load and then placed in Alpha I decell-rectifier service with the filament operating at 20.0 volts. The average rectifier load was 700 ma, and the output voltage was 38.0 kv. Twelve tubes were initially installed in two Alpha I decell rectifiers. At the time of the Alpha I shutdown only seven of these tubes had failed. The average life of the tube was 800 hr. The results of this test were as follows:

Classification of tube defects	Per cent of group
Mechanical failure of filament	71
Inverse emission	29

Although the electrical characteristics of this tube were good, it was impossible to determine the advantages of this design, owing to the structural weakness of the tube. When the Alpha I plant was closed in September 1945, the conversion program was canceled, and no further work was done to improve this design.

In summary, Westinghouse initially supplied CEW-TEC with the WL-616 tube, which was identical with the General Electric KC-4 and had all the weaknesses of the KC-4. Westinghouse then submitted a new design, the WX-3248, which was designed to replace the WL-616,

but initial tests indicated that this tube was inferior to the WL-616. Because of proposed changes in operating conditions, the WL-619 (WX-3260) with higher electrical ratings was next submitted. Initial tests of this tube were not favorable, and further design improvements were not made because of the shutdown of the Alpha I plant.

(c) Amperex Electronic Corp. Tubes. Since another source of supply for radiation-cooled rectifier tubes was necessary, Amperex Electronic Corp. was asked to submit an air-cooled rectifier tube that would be the mechanical and electrical equivalent of the General Electric KC-4. At a meeting with Amperex representatives it was learned that Amperex was then producing a British tube known as the "VU-504" (Fig. 5.10). Although this tube did not have so high an inverse rating as the General Electric type KC-4, it was thought that a test of this tube in CEW-TEC class service would supply useful design data for meeting the required specifications. The VU-504 differed from the KC-4 in that the inverse rating was only 90 kv, in that the rated filament voltage was 16.5 volts, and in that it had a mogul type of base. Six VU-504 tubes were given a 90-kv inverse no-load test by CEW-TEC, which all tubes passed satisfactorily. The tubes were placed in an Alpha I decell rectifier. Upon the application of plate voltage, one tube immediately displayed a continuous gas discharge. Since there were no other tubes available for replacement, the test was terminated.

As a result of the test, Amperex was advised that an inverse voltage of 90 kv was not satisfactory and that their new design should have a peak inverse voltage rating of 150 kv. Amperex was further advised that the low-drop plate characteristic of the VU-504 was desirable and that, if possible, this feature should be incorporated in the final tube design.

As a result Amperex submitted its KC4-A tube, the filament structure of which (Fig. 5.11) was similar to that of the VU-504 (Fig. 5.10). Amperex KC4-A tubes were placed in Alpha I decell-rectifier service with their filaments operated at 18 volts. The average life of the tube was 250 hr. The results of this test were as follows:

Classification of tube defects	Per cent of group
Mechanical failure of filament, filament failed at support and/or ceramic insulator broken	50
Gassy as shown by operation, arcing between anode and cathode	30
Inverse emission	20

This test showed that the design of the KC-4 filament structure was inherently weak and that a large percentage of failures would result from this feature alone. It was also found from the results of peak-inverse no-load voltage testing of these tubes that they had a rating of only 100 to 125 kv.

Because of the inherent filament weakness of the Amperex KC4-A tube, as described above, Amperex designed a new tube known as the "KC4-3." The filament design of this tube, as shown in Fig. 5.12, was similar to that of the General Electric KC-4, i.e., helical filament and spiral filament support. The emission characteristics and rating were supposedly the same as for the General Electric KC-4. These tubes were first received in October 1944 and were immediately placed in Alpha I decell-rectifier service. Several operational tests were made using the Amperex KC4-3. The average life of the tube was 68 hr. The results of one typical test with the filaments operated at approximately 20 volts follow:

Classification of tube defects	Per cent of group
Inverse emission	93
Cracked at seal press	7

The results of this test and the results of other similar tests indicated that the KC4-3 anode did not have enough thermal capacity to minimize or prevent inverse emission. Also, it was found that the inverse-voltage rating of the tube was only 100 to 125 kv, as indicated by the inverse-voltage no-load test.

Later some data were also obtained on these tubes operating in a Beta accell rectifier. The results indicated that the life expectancy of the KC4-3 in Beta accell service was approximately 1,000 hr, as shown by the KC4-3 survival curve (Fig. 5.13). This indicated that the life expectancy of the KC4-3 operating in Alpha I decell service would only be approximately 300 hr.

In summary, Amperex supplied CEW-TEC with two tubes, namely, the KC4-A and the KC4-3, to be used as replacements for the General Electric KC-4. Experience showed that these tubes were inferior to the General Electric KC-4. Amperex was advised that future designs would have to withstand 150-kv inverse-peak-voltage tests and provide a tube life comparable to the tube life of the General Electric KC-4. This work was discontinued because of the Alpha I shutdown.

(d) E. Machlett & Son Tubes. In conjunction with the other companies mentioned above, E. Machlett & Son was also requested to submit a radiation-cooled rectifier tube that would be the equivalent of the General Electric KC-4. Machlett laboratories submitted design

drawings of two tubes, the first being essentially an exact equivalent of the General Electric KC-4 and the second being Machlett's recommended design, known as the "ML-100." This tube differed from the General Electric design mainly in that a catenary type of filament construction was used, as shown in the photograph of this tube (Fig. 5.14). Review of the submitted drawings and recommendations made by Machlett laboratories resulted in a decision to purchase Machlett ML-100 rectifier tubes rather than the Machlett copy of the General Electric KC-4. The ratings of the ML-100 were as follows:

Filament:	
Voltage, volts	20.0
Current, amp	24.0
Maximum rating:	
Peak plate current, amp	1.0
Average plate current, amp	0.5
Peak inverse voltage, kv	150

In August 1944, the first ML-100 tubes were placed in service in an Alpha I decell rectifier. The first test was made by installing tubes in only two cubicles, but later this test was expanded to include 48 cubicles. The results of the 48-cubicle operation indicated that the life expectancy of the ML-100 tubes would be approximately 4,000 hr. Because of the results of this test, the ML-100 was adopted as a replacement for the General Electric KC-4. From approximately one year of operating experience it has been determined that the life expectancy of the ML-100 was approximately 2,600 hr, as shown by the ML-100 survival curve (Fig. 5.3).

An analysis of the tube failures resulting during this year of operation when the ML-100 was used in Alpha I decell rectifiers gave the following data:

Classification of tube defects	Per cent of group
Burned-out filament either because of inverse emission or evaporation; from experience it is reasonable to expect that most of these failures were due to inverse emission	56
Gassy tubes: this includes those tubes which were leakers and those which were determined gassy by test	41
Mechanical failures of filament: breaks occurring either at top or bottom of support	3

These data indicated that the life of the ML-100 was limited by two factors, namely, inverse emission and gas. The large percentage of inverse-emission failures can be partly attributed to the fact that, as in the case of the General Electric KC-4, the ML-100 filaments were operated at less than rated voltage (18.0 to 19.0 volts) until May 1945, at which time the filament voltage was raised to 20.0 volts. A large percentage of the gas failure was found to be due to gas being evolved by the top filament ceramic insulator shown in Fig. 5.14. In the first ML-100 tube, quartz had been used for this insulator, but owing to a shortage of quartz it became necessary to substitute a ceramic insulator. This insulator was being bombarded by electrons from the filament during operation, and because of this bombardment, gas was evolved in the tube.

Machlett laboratories initiated a change in the filament structure to minimize mechanical failure of the filament at the filament support and to decrease manufacturing cost. This filament structure is shown in Fig. 5.15. The filament structure shown in Fig. 5.16 is similar to Fig. 5.15 except that the top filament insulator is shielded from electron bombardment. This design change was recommended by CEW-TEC to minimize the number of tubes failing owing to gas, as explained above. At this writing sufficient operating data have not been collected for evaluation of the later design.

The change from a quartz insulator to a ceramic insulator, as explained above, partly accounted for the discrepancy in the life expectancy of the ML-100 from 4,000 hr on the initial test to 2,600 hr after operation for one year. It is pointed out, however, that the initial test was made with the ML-100 operating in a rectifier with load current similar to that of the KC-4 but that before the close of operation it became necessary to substitute ML-100 in place of KC-4 to meet the higher load required by plant operation. At the end of this one-year period of operation essentially all the Alpha I decell rectifiers were operating with an actual load current of 1.0 amp, but during the initial test period the same rectifiers had operated at only 0.6 amp. Owing to this change in load current it was impossible to make a direct comparison between the average life of the Machlett ML-100 and the General Electric KC-4.

Because of the anticipation of higher drain currents, Machlett was requested, along with other manufacturers, to submit a design of a tube having higher current rating and higher inverse-voltage rating for conversion operation. Machlett thereupon submitted the design of the Machlett ML-200. The rating of this tube was as follows:

Filament:	
Voltage, volts	21.0
Current, amp	31.0
Maximum rating:	
Peak plate current, amp	2.5
Average plate current, amp	0.55
Peak inverse voltage, kv	150

In May 1945, Machlett submitted samples of the ML-200 for test. The filament construction of the ML-200 was similar to the filament construction of the ML-100, and these tubes were initially tested at CEW-TEC at 200-kv peak inverse no-load. The tubes that passed this test satisfactorily were used to equip the Alpha I decell rectifier in one cubicle, the filaments being operated at 20.0 volts and the average cubicle load being 600 ma with a regulated output voltage of 38.0 kv. After these tubes had operated under these conditions for approximately 1,500 hr, two of the tubes failed because of gas. These tubes were replaced, and the test was continued 800 hr until the Alpha I shutdown.

In order to obtain further test information, six ML-200 tubes were installed, in November 1945, in a decell rectifier in one of the Beta cubicles. The filaments were operated at 18.5 volts. After 4,000 hr of operation in this class of service only one of these tubes had failed. This failure had occurred after approximately 1,200 hr of operation and was due to gas. Although the test was very encouraging, the sample, which was only six tubes, was too small to permit drawing any definite conclusions. An accurate evaluation would require an extended test using 48 cubicles.

(e) Summary. As a result of experience with the various types discussed above the conclusion has been drawn that a radiation-cooled rectifier tube to be suitable for CEW-TEC class of service required higher inverse-voltage and current ratings than did the KC-4. Such tubes were in a state of development at the time of the Alpha plant shutdown. The plate-current characteristics of such tubes have been compared with those of the KC-4 and WL-616 types in Fig. 5.17.

2.2 Water-cooled Rectifier Tubes. (a) General Electric Company Tubes. The analysis of water-cooled rectifier tubes will be made in general for the decell rectifier of the Alpha II process because water-cooled rectifier tubes were submitted to test in this class of service. All the tubes in the initial installation in the Alpha II decell rectifier were either GL-562 (Fig. 5.18) or GL-605, as furnished by General Electric. These two tube types were identical; the different type

numbers served to indicate that the GL-562 was test-selected from a group of GL-605 tubes. Electrical characteristics of the GL-562 tube are shown in Fig. 5.19.

The average life of this tube in Alpha II decell-rectifier service has been found to be 3,000 hr, as shown by the GL-562 survival curve (Fig. 5.20). This curve was plotted in the same manner as were the curves for the air-cooled rectifiers described in a previous section.

Analysis of tube failures during the period in which Alpha II decell rectifiers were operated showed the following:

Classification of tube defects	Per cent of group GL-562	Per cent of group GL-605
Burned-out filament section wherein the filament structure had been badly distorted	79	75
Burned-out filament owing to either inverse emission or evaporation	5	13
Open filament lead	6	10
Gassy tubes	5	2
Miscellaneous	5	0

The above data indicated that the life of these tubes was not limited by filament evaporation but by inherent tube weaknesses (filament) and results of faulty manufacturing techniques (gas and filament-lead burn-out). In an effort to improve the filament design General Electric made certain changes in the GL-562. The new-design tube was known as the "GL-697" (Fig. 5.21). It differed from the GL-562 in that the anode thickness was increased from ⅛ to ¼ in. and the filament corona-cap design was changed.

The change in the thickness of the anode wall was made to provide better thermal conductivity and more uniform heating in the anode and thus to reduce the possibility of hot spots and anode outgassing. Tests of earlier experimental tubes, to be discussed in a later section, had indicated the desirability of this feature.

In the original GL-562 and GL-605 (Fig. 5.22) designs it had been found that the corona cap, which protected the end of the filament structure, was so small that it was possible for the filament strand to short to this cap. It was also found that this corona cap was not securely anchored to the filament push rod and would rotate so that its support member could come in contact with two strands of the filament, thus shorting this portion of the filament. As a result, in the design of the GL-697 the spacing between the filament support

hook and the inside of the corona shield cap was made 0.180 in. instead of 0.118 in. as had been done previously in the GL-562. At the same time the spacing between the center filament push rod and the filament support hook was increased from 0.0445 to 0.090 in.

The results of the change were indeterminate since the number of tubes received by CEW-TEC was insufficient to conduct a test of this design.

(b) Westinghouse Tubes. As in the case of the radiation-cooled rectifier tube, it was felt that an additional source of supply was necessary for the water-cooled type. Therefore Westinghouse was asked to submit a water-cooled rectifier tube that would be the physical and electrical equivalent of the General Electric type GL-562.

Physically the tube submitted was interchangeable with the General Electric GL-562. The electrical characteristics, as given by Westinghouse, were identical with those of the GL-562 except that the peak inverse voltage rating was given as 65 kv and the peak plate dissipation as 85 kw (5 min maximum).

The initial test of these tubes at CEW-TEC revealed that a large percentage of these tubes was so gassy that few could be placed in operation in the plant. The remaining sample tubes were returned to Westinghouse, and the program for the development of this tube was stopped owing to the shutdown of the Alpha II buildings.

(c) E. Machlett & Son Tubes. In addition to the other companies mentioned above, E. Machlett & Son had also been requested to submit a water-cooled rectifier tube that would be the equivalent of the General Electric GL-562.

The first test sample was submitted to CEW-TEC in January 1945 and was known as the "ML-101" (Fig. 5.23). This tube had a two-strand catenary filament 0.025 in. in diameter giving a filament characteristic of approximately 24 amp at 22 volts. This tube had an emission-limit characteristic that was not so sharp as the GL-562. The plate-voltage drop was very low compared to the GL-562. Since such a low plate-voltage drop was very desirable for rectifier service, Machlett was requested to furnish a number of these tubes. However, filament characteristics matching those of the GL-562 were desired, i.e., a filament current at 22 volts of 52 amp.

The filament of the ML-101 was redesigned, a filament wire 0.0405 in. in diameter and of such a length as to give 52 amp at 22 volts being used. A filament volt-amp characteristic identical with the GL-562 and an emission characteristic that was essentially the same as that of the GL-562 resulted.

In March 1945 this filament structure was modified by Machlett by reducing the diameter of the cathode circle and by extending the fila-

ment strand to form a loop in the end cap of the anode. The first of these changes resulted in a sharper cutoff, but the second tended to give more uniform anode dissipation. This resulted in a tube having the following ratings:

Filament:	
Voltage, volts	22
Current, amp	52
Maximum rating:	
Peak plate voltage, kv	60
Peak plate current, amp	7.5
Average plate current, amp	5.0
Average plate dissipation, kw	30
Surge-limiting operation:	
Peak voltage, kv	60
Peak plate current, amp	7.5
Average plate dissipation, kw	30
Peak plate dissipation (for 10 sec), kw	60

Tests were in progress at the time of the Alpha plant shutdown, and although such tests appeared very promising, no definite conclusions as to average life of the ML-101 were drawn. Electrical characteristics of the ML-101 tube are shown in Fig. 5.24.

(d) Amperex Electronic Corp. Tubes. Sample water-cooled rectifier tubes equivalent to the GL-562 were supplied by Amperex Electronic Corp. The tubes supplied were a direct copy of the GL-562. Emission tests made to determine the cutoff ratio of the Amperex tube disclosed that the filament emission was erratic and tended to drift. Samples of these tubes that had passed initial high-voltage tests were placed in service in the Alpha I cubicles. These tubes performed satisfactorily, but the number of tubes actually tested was small in comparison with the total number of tubes submitted for test. The tests showed that in general the filament structure of the Amperex tube was weak and that the tubes tended to be gassy. As a result of this test a development program was initiated by Amperex, and a new tube known as the "Amperex 61" (Fig. 5.25) was designed; however, samples of this tube had not been received at the time of the Alpha I shutdown.

(e) Federal Telephone & Radio Corp. Tubes. The Federal Telephone & Radio Corp. was also an alternate source of supply for water-cooled rectifier tubes. This company furnished CEW-TEC their F-562, which had physical and electrical characteristics equivalent to those of the GL-562. Federal also designed and submitted for test their F-660

(Fig. 5.26), which they believed to be superior to the F-562. The F-660 differed from the F-562 in that the anode wall had been increased to 0.250 in., in contrast to the 0.090-in. anode of the F-562. It was felt by Federal that the increased thickness of the anode wall would provide better thermal conductivity in the anode and better heat dissipation from the anode to the cooling water during periods when this tube, acting as a limiter, was operating emission-limited. Tests indicated that this increase in thickness of the anode wall increased the average anode dissipation from 20 to 40 kw under steady-state operation and that under surge-limiting operation the peak anode dissipation could safely be 60 kw. The Federal type F-660 was widely used as a replacement rectifier tube in the Alpha II channels and was found to be one of the most satisfactory water-cooled rectifier tubes used during plant operation. The survival curve for the F-660 indicates a life expectancy of 5,000 hr for this tube when used in the Alpha II rectifier service and shows this tube to be superior to the General Electric GL-562. A comparison of the two tubes is shown in the survival curve (Fig. 5.20). The ratings of the F-660 were as follows:

Filament:	
Voltage, volts	22.0
Current, amp	52
Maximum ratings:	
Rectifier operation:	
Peak inverse voltage, kv	50
Peak plate current, amp	7.5
Average plate current, amp	2.0
Average plate dissipation, kw	40
Surge-limiting operation:	
Peak forward voltage, kv	60
Peak plate current, amp	7.5
Average plate dissipation, kw	40
Peak plate dissipation, kw	60
(Duration of plate dissipation greater than 40 kw shall not exceed 5 sec)	

Electrical characteristics of the F-660 tube are shown in Fig. 5.27.

3. CAPACITOR FAILURES

The line-terminating capacitors of the Alpha I decell rectifier were a source of considerable trouble. This capacitor consisted of two sections connected in series and mounted in a common case, each

section rated at 25-kv and each section insulated from the case for 30 kv. In its application a divider was not provided for equalizing the voltage across each section. The case of the line-terminating capacitor was connected to the case of the filter capacitor for the rectifier in order that a common grounding switch could be used for the rectifier and in turn permit a common grounding switch to be used for the two capacitor cases. As a result of this interconnection between the line-terminating capacitor case and the filter-capacitor case the insulation of one section of the line-terminating capacitor to the case was subjected to the full supply voltage on limiter-tube gas kicks. The voltage was in excess of the 30-kv rating for the insulation between the capacitor and the case.

The failure rate for the line-terminating capacitor caused by this connection increased to 40 per month before a single-section capacitor could be secured with a rating of 50 kv to the case. After the two-section capacitors were replaced with the newer style single-section capacitors, the failure rate decreased to essentially zero.

In the Beta equipment the same type of two-section line-terminating capacitor was used and was also the source of considerable trouble. The application was essentially the same as that in Alpha I, and likewise the failure rate was excessive, rising to approximately 10 per week. As in the case of Alpha I, it was necessary to replace this capacitor with a single section rated at 50 kv. After this had been done, the rate of failures immediately dropped to essentially zero.

In the Alpha II equipment, because of experience gained with Alpha I and Beta, the initial capacitors supplied with the equipment were the single-section type, and no trouble was experienced.

The filter capacitors for the accell- and decell-rectifier supplies in Alpha I, Alpha II, and Beta equipment were all operated within their voltage ratings and did not have an excessive failure rate. The failure and replacement rates were less than 1 per cent per month of the total number of capacitors in operation. In the Beta equipment the capacitors were the double-section type provided with a voltage divider connected across them to equalize the voltage per section. Generally it was found after the failure of a capacitor that the voltage divider used to equalize voltage across the sections ha [illegible]; this was probably the cause of the capacitor failures.

4. FILTER-CIRCUIT CHARGE AND DISCHARGE RESISTORS

The condenser charge and discharge resistors used in the filter circuit of the accell rectifier in the Alpha I process were a source of considerable trouble, as has previously been discussed. These resistors were mounted on impregnated wood supports, and overheating

of the resistors caused numerous fires in the high-voltage cubicle. Such fires not only destroyed the resistor and its support but in many cases destroyed other wiring in the cubicle. Considerable time was required to effect replacements. Such fires caused considerable loss of production since the number of these fires in the Alpha I process averaged approximately 55 per month and at one time reached as high as 120 per month.

In the case of Alpha II the greatest cause of resistor trouble was due to the line-terminating resistors for the decell rectifiers. During operation, when a fault occurred at the tank, this resistor was required to carry 3 amp for a period of approximately 1 sec until the overload relays tripped. Although a fault current of 3 amp existing in the resistor was equivalent to only 30 watts dissipation in the resistor, which was rated at 750 watts, it was found that owing to oscillation these resistors would operate at a red heat. The exact amount of power dissipated by these resistors was never determined. Various attempts were made to correct this trouble. A discussion of the experimental resistors used will be given elsewhere in this volume. None of these experimental resistors were used for plant-wide operation.

The resistors used in Alpha II for limiting the charge and discharge current were of ample rating since they were required to carry a load current of only 2.2 amp and were rated for steady-state operation of 2.57 amp. However, a considerable number of the discharge resistors were lost during operation because in many instances the grounding switches would fail to open before the supply was energized, thus causing these resistors to carry an excessive current.

In the Beta process the discharge resistors would burn out at or near the mid-point of the winding of the resistors. After a thorough investigation it was found that these failures were caused by arcing from one rectifier tube socket to the mid-point of the resistor. This source of failure was eliminated by moving the resistor to provide ample sparking clearance.

5. INDUCTION VOLTAGE REGULATORS

The induction voltage regulators in the Alpha I and Beta process were in all cases operated at or below their name-plate rating. As a result no failures caused by overloading of these regulators were experienced. However, in Alpha II the decell induction voltage regulator was operated at 115 amp, 615 volts, but had a rating of 109 amp, 620 volts. This overload necessitated additional forced-air cooling to prevent overheating of this particular regulator. Several regulators were burned out before a special air duct could be designed and in-

stalled in the cubicle to provide additional forced-air cooling. With the addition of this special air duct it was found that this regulator could be operated safely at 130 amp, 620 volts, which was more than ample for the requirements of operation.

Throughout the plant considerable trouble was experienced with induction voltage regulators, owing to excessive bearing friction or bearing misalignment. Also, in each of the processes several regulators had to be replaced because of the presence of foreign objects lodged in the winding. The presence of such foreign objects could be attributed only to carelessness during the installation of the equipment and maintenance of the equipment after installation because these objects were, in general, bolts and nuts normally used in the installation of the regulators and associated equipment. These foreign objects caused two types of failure in the regulator, namely, insulation breakdown in the regulator winding and blocking of the rotor, which caused the regulator drive motor to overheat and burn out.

A casual inspection of the attached summary of reports of troublesome features would at first seem to indicate that these regulators were not a major source of difficulty since in Alpha I, for example, only approximately 2.3 per cent of the regulators in service had to be replaced per month owing to these failures. However, it should be remembered that the number of replacements was kept small only at the expense of considerable maintenance time, which had to be spent to service these regulators. Because of the peculiar construction of the high-voltage cubicle and the regulators, the mounting of the regulators in the high-voltage cubicle was such that it was necessary to remove the regulator from the cubicle for even such minor maintenance as greasing the bearings.

6. CONTACTORS

The lack of relay coordination caused the main 460-volt contactors in all three processes to be a source of considerable trouble. The relays used with this contactor for overload protection were plunger overcurrent relays, and it was extremely difficult to coordinate them with the magnetic trip attachment of the air circuit breaker used at the unit substation. Owing to this difficulty in coordination, if short-circuit currents of high magnitude were experienced, these contactors would frequently act because of such fault currents, which could be several times the interrupting capacity of the contactors. This, in general, would destroy the contactor and in many cases other equipment located adjacent to it.

The fault current mentioned above was usually caused by phase-to-phase arc-overs in the contactor that supplied the high-voltage rectifier. Although the rectifier contactor had a name-plate rating that was higher than the steady-state load current, the heavy-duty cycle and the many faults occurring in these rectifiers resulted in a high failure rate for the contactor, especially in the Alpha I and Beta processes. This point has also been discussed in Chap. 3, Sec. 5.2. The failure rate for the rectifier contactors increased to approximately 10 per cent per month, and for at least 25 per cent of these failures it was necessary to rework the cubicle main power contactor. The excessive contactor-failure rate was reduced to essentially zero by the installation of 150-amp step-start contactors and by the addition of the recycler circuit to prevent rapid-fire operation of the contactors.

Numerous rectifier-tube failures were also experienced owing to failure of the rectifier contactors. In several cases the rectifier contactor would fuse closed, thus preventing the operator from deenergizing the rectifier by means of its normal control system. The cubicle operator would then use the cubicle main power contactor as a means of deenergizing the rectifier. When the main power contactor was next reenergized, the high voltage was immediately applied to the rectifier tubes before filament voltage had been applied and before the grounding switches had been energized. This shorted the rectifier and allowed the tubes to come up to operating temperature with excessive load current, causing emission-limiting failure of the rectifier tubes. This type of trouble was so serious in Alpha II that a change was initiated to interlock the high-voltage contactor with the main power contactor in such a manner that the main power contactor was deenergized. However, this change was not put into plant operation because General Electric could not supply the required auxiliary contacts prior to the time the buildings [illegible]re shut down.

In the Alpha II cubicle a magnetic [illegible]t breaker was supplied in the rectifier-filament circuit; this [illegible] Heineman breaker rated at 20 amp, 460 volts. This rating w[illegible]ot ample for the normal filament current. Later cubicles were equipped with a 35-amp breaker, and breakers were supplied to be substituted in the original cubicles upon failure of the 20-amp breaker. However, the 35-amp breakers failed owing to loose inside connections. The construction of the breaker was such that it was impossible to tighten the connections without removing the breaker from the cubicle. Since this resulted in considerable loss of production time, a new type of breaker was ordered of different construction which could withstand the vibration due to the step-start contactors without developing loose connections.

7. STEP-START RESISTORS

In both the Alpha I and Alpha II equipment the step-start resistors used in the primary circuit of the high-voltage rectifier had an abnormally high failure rate. This high failure rate was attributed to two causes: (1) the heavy-duty cycle imposed upon the resistors and (2) the fact that the resistors remained in parallel with the main rectifier contactor while this contactor was energized. The contact resistance of the main contactor was high enough so that the step-start resistors carried a sufficient current to cause them to overheat unless the contacts of the main contactors were kept exceptionally clean. In order to reduce failures due to this shunting effect of resistors, CEW-TEC rewired the main contactor and step-start contactor circuit in such a manner that the main contactor would drop out the auxiliary contactor as soon as it had been energized. Failure of the step-start resistors by burning out usually initiated an arc that tended to set fire to cables adjacent to these resistors and, in many cases, to initiate a phase-to-phase flashover at the contactor. Such phase-to-phase flashovers were discussed in Sec. 6.

In the Alpha I plant it became necessary to replace as many as 450 of these resistors per month, and in the Alpha II plant at one time the number of resistors replaced became so great that it was impossible to obtain sufficient replacements.

To prevent this type of failure both the Alpha I and the Alpha II cubicles were rewired so that the resistors would be out of the circuit during normal operation, being dropped out by auxiliary contacts on the main rectifier contactor. In Alpha I the resistors supplied with the original equipment were replaced by 180-watt resistors at the same time that the step-start contactors were replaced by 150-amp contactors (Chap. 3, Sec. 1). After these changes were made, the failure rate of these resistors in the Alpha I equipment fell to essentially zero.

During the period in which it was impossible to obtain replacement resistors for the Alpha II cubicles, it was decided to try operating the cubicles without the use of the step-start circuit. Results of this experimental study will be discussed in Chap. 6, Sec. 13. After the Alpha II cubicle control circuits had been rewired, as described above, no further difficulty was experienced with these resistors. In the Beta cubicles failure of these resistors was no higher than would normally be expected.

8. RECYCLERS

After the recyclers, described in Chap. 3, Sec. 5.2, had been installed, the difficulties experienced with them were relatively few.

The recycler circuit supplied by General Electric and used in the Alpha II cubicles was initially so adjusted that, if an overload occurred, the rectifier contactors would open and would be reclosed within 2 sec. If a second overload followed within 0.5 sec after this reclosure, the contactor would again be dropped out, and it could not be reenergized by the recycler circuit. This necessitated close supervision by the cubicle operator whenever the recycler was not functioning properly. A study was made of outages due to lockout in the recycler circuit. It was found that the timers could not be set properly as originally installed in the cubicle and that one of the auxiliary contacts in the recycler circuit was being severely burned in operation. A complete report of this study is given in Chap. 6, Sec. 11.

As a result of this study a change was initiated to replace the contact that was being burned by a heavier contact and to replace its springs with a heavier spring in order to prevent bouncing of this contact. Also, an experimental change for 48 cubicles was decided upon which consisted of making adjustments for greater accuracy by providing resistors in the recycler timer.

The first recyclers in the Beta cubicles were designed and installed by CEW-TEC. After the installation of these recyclers, troubles and failures experienced with them were nominal.

9. GROUND SWITCHES

The high-voltage cubicles were supplied with grounding switches used for discharging the filter capacitors and the line-terminating capacitors in the high-voltage circuit. These switches consisted of a Micarta tube approximately 30 in. in length to provide sufficient clearance for the high-voltage circuit. The movable contacts were mounted on an insulating plunger rod moving in the center of the tube. This plunger was actuated by means of a magnetic solenoid energized by the control-power switch.

Several of these switches failed owing to arc-overs between the high-voltage contacts caused by the plunger binding. These arc-overs did not allow the contacts to open sufficiently. Binding of this plunger before the magnetic circuit of the solenoid was fully closed tended to reduce the reactance of the coil to a value so low that the current drawn by this coil would overheat it and cause failure of the coil. Since failures of the grounding switch were of the order of only 0.5 per cent of the total number of switches in operation per month, redesign and replacement of these switches was not felt to be justified, and these failures were tolerated.

10. METERS AND RESISTORS

In the Alpha I equipment, meters used in the high-voltage rectifier circuit gave little trouble during operation. It was found that only approximately 1 per cent per month of these meters had to be replaced. Failure of the meters was usually due to high-voltage surges, which in many cases had occurred after the meter-surge protective equipment had failed. The failure rate of these protective devices was approximately the same as the failure rate of the meters. The major portion of the failures of the voltmeter multiplier was due to mechanical rather than to electrical causes. The voltmeter multipliers were long wire-wound resistors having no protective covering. As a result the wire on these resistors was often damaged by the maintenance personnel working in the high-voltage cubicle.

The voltmeter multiplier for the Alpha II equipment consisted of a series combination of small carbon resistors giving a total resistance of 25 megohms. The multiplier was used with a meter having a 2-ma movement, the accuracy of which was within 2 per cent of a full-scale calibration of 50 kv. It was found, however, that after a few weeks of operation, readings of these meters were from 5 to 10 per cent high. This was caused by dirt that collected on the meter resistor and changed its resistance value. This condition was corrected by calibrating the meters with a portable standard at regular intervals.

The ammeter used in the decell-rectifier circuit was the greatest source of trouble in the Beta cubicle. The protective choke for this meter had been placed on the grounded side of the meter, and a resistor, which formerly had been used to operate a d-c overload relay, was connected between this choke and ground. This resulted in a long ground lead with a high surge impedance. The value of this impedance was so high that a potential was built up at the meter during sparking at the tank to a value high enough to spark over from the meter movement to a grounded portion of the high-voltage cubicle.

A thorough investigation of this trouble was made because the failure of the meter was accompanied by an explosion that shattered the meter case and glass in front of the cubicle, thus endangering the operator. This explosion was thought to occur when arcing from the meter movement to the case mounting screws occurred. At the point of this arcing the bakelite case would show evidence of having been charred, and presumably gas liberated under this heat would be ignited by the arc causing the explosion.

To remedy this situation the choke on the grounded side of the meter was first moved to the opposite side of this meter. This change was

an improvement, but failures still occurred. The resistor discussed above was then removed from the circuit, and the grounding lead was shortened. After these two changes had been made no more failures of this type were reported. In general, after the corrections discussed had been made, meter replacements per month were of the order of 2 per cent.

11. RELAYS

Failures of the overload protective relays were one of the major sources of trouble for some time after starting operation. Most of these failures occurred in the instantaneous-trip attachment of the IAC overcurrent relays used in the primary of both high-voltage supplies. The duty cycle imposed on this instantaneous attachment was many times that for which it had been designed. These failures usually occurred because of breakage of the composition head that supported the contacts or because the contacts became misaligned by repeated stress. Another source of failure was the disk, which served as a movable contact on the plunger. The first-mentioned defect was corrected to some extent by the use of a more strongly reinforced head, and the second defect was corrected by replacing the movable-disk contact with one constructed of heavier material.

In the Beta equipment more serious damage to the relay than the breaking of parts occurred when these relays failed. The failure of the composition head would allow the contact to be forced against the grounded case of the relay. This would burn out the holding coil of the relay circuit. A change was made whereby this coil was placed in the grounded side of the control circuit, thus preventing failures due to the case.

In the Alpha I equipment the overload relays were originally wired in such a manner that the instantaneous contacts were required to break the current of an auxiliary relay coil. Excessive burning of these contacts resulted. The circuit was rewired in such a manner that the overload-relay contacts acted only to energize this auxiliary circuit. The circuit was deenergized by contacts on a second auxiliary relay. This change greatly reduced the burning of the instantaneous contacts. The installation of recyclers also considerably reduced the failure rate of the overload relays by decreasing the duty cycle imposed on them. The failure rate was decreased owing to the elimination of the possibility of rapid-fire relay-contactor operation.

In Alpha II the induction time element of the overload relay was operated within its current rating, but the instantaneous element was operated at 15 amp and was rated at a maximum of only 12 amp. This made calibration difficult and caused the plungers to have a greater

degree of travel before closing the contact. This, in turn, caused even more failures in Alpha II due to breaking of the contact head. When the spare relays were ordered for this equipment it was found that General Electric had discontinued the manufacture of this type of relay, and a new type was shipped instead. The manufacture of spare parts for the old-type relay had also been discontinued. The new type was a definite improvement over the old type, but unfortunately some 480 relays were in operation for which spare parts could not be secured. Fortunately at this point Alpha II plant operation was discontinued.

12. MAINTENANCE EQUIPMENT AND PROCEDURE

In order to maintain the various high-voltage rectifiers and to reduce the loss in production time to the minimum, various pieces of specialized maintenance equipment were required. Some of this equipment, such as the dummy load, air-cooled-tube tester, relay checker, etc., is described in this section.

It was felt before the plant was first placed in operation that it would be very desirable to check the various high-voltage supplies by substituting a dummy load for the actual mass-spectrograph load. Actually two types of loads were used in the plant for this purpose. These loads presented to the rectifier only a steady-state load and did not simulate sparking and short-circuit conditions such as existed in the mass spectrograph during actual operation. These dummy loads, however, proved to be extremely useful during the initial start-up period at the plant since they offered a means of checking the high-voltage equipment before it was actually connected to the mass spectrograph. In this check each cubicle was inspected for contactor and control-circuit operation, the high-voltage output of the rectifier, the regulation range of the power supply, the ripple voltage on the high-voltage supply lines, and the accuracy with which the protective relays had previously been set. During the first few months of Alpha I plant operation this check was made at the end of each run. However, as production increased and the period between tank runs was decreased, it became impractical to make this check, and since the high-voltage equipment at the end of each run had just completed approximately two weeks of successful operation, it was felt that it would not be necessary to continue the practice of checking the equipment at the end of each run. Therefore the use of the dummy load for interrun checks was discontinued, and the load was used only when the equipment indicated troubles that were difficult to find without the application of the load. The dummy loads were also used for special tests,

such as an over-all regulation check and regulation checks of the rectifier, using different types of experimental rectifier or regulator tubes.

Two types of dummy loads were utilized at the plant. The first of these was a resistance load, and the second was an electronic load. The resistance load consisted of a bank of resistors and load-selector switches mounted in a metal-clad enclosure that was on rubber-tired casters. The resistors were forced-air-cooled by a blower mounted in the enclosure and, depending on the switch position, presented a load to the high-voltage supply of 0.2, 0.4, or 0.8 amp at 35 kv.

The usefulness of this resistor load led to the development of an electronic dummy load that was continuously variable from no-load to 200 per cent of the rectifier rated current at a constant rectifier-output voltage. This load consisted of two air-cooled high-vacuum diode tubes connected in parallel and supplied with a variable filament-voltage supply. The tubes were forced-air-cooled by means of a centrifugal blower mounted in the dummy-load enclosure. The diode tubes were operated emission-limited. By varying their filament voltage they could be made to present to the high-voltage rectifier a continuously variable load from 0 to 2.2 amp at a rectifier output of 35 kv. This electronic dummy load was also mounted in a metal-clad enclosure that was on casters.

Both the resistance and the electronic dummy loads were supplied with control and protective equipment and with flexible high-voltage x-ray cable for connection to the high-voltage rectifiers.

At the time of the installation of the high-voltage cubicles the General Electric Company furnished CEW-TEC with a tube tester for the radiation-cooled rectifier tubes. General Electric recommended that in any one rectifier only those tubes having similar emission characteristics should be used. This tube tester made possible classification of tubes according to their emission characteristics for proper selection as replacements in the high-voltage rectifiers.

The tube tester consisted of a single-phase 460/6,500-volt transformer, which was used to supply anode voltage, a single-phase 460/115-volt transformer, which was used to supply control power, and a single-phase 115/22.5-volt transformer, which supplied filament power to the rectifier tube under test. A Variac was provided to control the filament voltage of the tube under test in order that this voltage might be varied from approximately 0 to 21 volts. A plate contactor operated by a manual switch in the control-power circuit was used to energize the 460-volt supply to the plate transformer for a definite time cycle. Energizing was accomplished by two time-delay relays with interlocking contacts connected in the plate-contactor

control circuit. When the plate-contactor control switch was closed manually, the plate supply was energized, placing 6,500 volts on the anode of the tube under test for a period of 0.1 sec, as determined by means of the time-delay relay. At the end of 0.1 sec the plate transformer was deenergized by the first relay, and a timing cycle was initiated. At the end of 1.0 sec the plate transformer was reenergized by the second relay, and this cycle of 0.1 sec with power on and 1.0 sec with power off continued until the manual control switch was placed in the off position.

During the time the plate circuit was energized, the plate or emission current was indicated by a crest ammeter. For the rectifier tubes a standard was established for the emission current, as determined by the crest ammeter for a specified filament voltage.

The emission test was made on a tube by varying the filament voltage with the Variac until the standard value of emission current was established. The tube was then classified according to its filament-voltage deviation from the standard filament voltage. This classification was in increments of plus or minus 1 per cent with respect to the standard filament voltage. Replacements were made in the high-voltage rectifiers in such a manner that in any one rectifier only tubes of the same classification were used.

A second tube tester for use in initial tests of the radiation-cooled voltage-rectifier tubes was also supplied by General Electric. This tube tester was designed to check the inverse-voltage characteristic of the replacement rectifier tubes as well as of questionable tubes found in plant operation.

The inverse-voltage tube tester consisted of the following principal units: (1) rectifier transformer, (2) control-panel stand, and (3) capacitor rack.

The rectifier consisted of a plate transformer with separate winding for voltage measurement, filament transformer, and tube socket (for the tube under test), and a protective film cutout. The plate transformer and the filament transformer were assembled on separate cores, and both transformers were mounted in an oil-filled tank. The plate transformer was rated single phase, 60 cycles, 25 kva, 66,000/694 volts. The filament transformer was rated single phase, 60 cycles, 0.55 kva, 220/22.8 volts. The tube under test was mounted in a tube socket, which was supported by a porcelain bushing located on the cover of the transformer tank. The connections from the filament transformer to the tube socket were brought out of the transformer tank through the porcelain bushing. A separate winding for a voltmeter was supplied on the plate-transformer core with both ends of the winding brought out to terminals on the transformer cover. The voltmeter coil was con-

nected to a crest voltmeter, which was used as a means of determining the voltage applied to the tube under test. The design of this voltmeter coil and its location on the transformer core were chosen so that they would accurately indicate the voltage supplied by the high-voltage winding of the plate transformer.

The capacitor-rack assembly, which was constructed of oil-treated maple, supported the equipment that was connected in the plate circuit of the tube under test. The equipment mounted on this rack consisted of voltage-doubling capacitors, a discharge switch, voltage-equalizing resistors, a discharge resistor, a current-limiting resistor, and a gas-kick-signal resistor.

The control-power stand consisted of a control panel that contained the necessary switches, meters, circuit breaker, and Variac for controlling the operation of the test set. The various contactors, relays, vacuum tubes, and induction regulators were also mounted on this control stand.

The operation of this tube tester was as follows: When the main-line switch and circuit breaker were closed, 460 volts was applied to the tube-tester control-power transformer. This energized the 115-volt control circuit. When the Variac, which controlled the tube-filament voltage, was placed in the minimum voltage position and when all high-voltage interlocks were closed, the filament transformer was energized, and the induction voltage regulator in the primary of the plate transformer was automatically run back to its minimum voltage position. This minimum voltage was 33⅓ per cent of the voltage rating of the plate-transformer primary winding. When the induction voltage regulator had reached its minimum position, power was applied to the plate-voltage transformer. This voltage could be manually increased by means of the induction voltage regulators until the desired test value was reached. By means of this induction voltage regulator the secondary voltage of the plate transformer could be continuously varied from 22,000 to 66,000 volts.

The high-voltage winding of the plate transformer was connected to the plate of the tube under test and to the voltage-doubling capacitor in such a manner that the tube under test served as a rectifier to charge the voltage-doubling capacitor. This capacitor was charged to a voltage equal to the peak secondary voltage of the transformer. On the reverse half cycle the capacitor voltage was added to the peak voltage of the transformer secondary, and the resultant voltage was applied in an inverse direction across the tube under test.

A crest voltmeter was provided for measuring the inverse test voltage applied to the rectifier tube. The crest-voltmeter circuit consisted of two half-wave rectifier tubes, one tube being used for the

positive portion of the voltage wave and the other tube being used for the negative portion of the wave. These rectifiers were connected to the voltage-measuring coil wound on the plate-transformer core and served as rectifiers charging two condensers to the peak value of the voltage wave. These capacitors were series-connected; the meter therefore indicated the sum of the capacitor voltages. The crest voltmeter was calibrated to read 150 kv full scale.

If the tube under test was unable to withstand the test voltage applied, a gas kick occurred. A surge-detector circuit, which consisted of a thyratron-controlled solenoid-operated counter, was incorporated in the test set to indicate such gas kicks. When the tube under test gas-kicked, the reverse current of the gas kick supplied a signal to the grid of the thyratron, which caused it to fire, thus operating the counter. The counter, in turn, recorded the number of gas kicks taking place during the period of the inverse-voltage test. In plant operation this tube tester was used to determine whether tubes were suitable for use as replacements in the high-voltage rectifiers. The test procedure used for these tubes and a similar one for water-cooled rectifier tubes are discussed after a description of the high-voltage water-cooled test set has been given.

The test equipment supplied by General Electric for testing high-voltage water-cooled tubes consisted of the following principal parts: (1) rectifier, (2) control cabinet, and (3) tube test stand. The components were located in two areas, each of these areas being enclosed by a fence 8 ft high and having entrances interlocked with the high-voltage control circuit in order to protect personnel entering the areas. The first area, approximately 5 by 12 ft, contained rectifier equipment that was identical to the Alpha I decell rectifier described in Chap. 2, Sec. 2. This rectifier had a maximum no-load voltage rating of 42 kv and a maximum full-load current rating of 1.0 amp. The control cabinet, which was 30 in. wide, 46 in. deep, and 61 in. high, was mounted in the same area, with its front panel flush with the fence of the enclosure so that the operator could operate the controls from outside the test area.

Adjacent to the area described above was a second enclosed area, approximately 7 by 12 ft, which contained the tube test stand. The entrance to this area was interlocked with the necessary circuits to prevent voltages from appearing at the tube test stand when the area was entered. The test stand consisted of rectifier filter capacitor and grounding switch, a suitable water jacket, water coil and water-flow indicator for the tube under test, the necessary filament transformer, and a gas-kick indicator.

The interlock on the entrance to the tube test-stand enclosure was connected to the control circuit of the test set in such a manner that both plate and filament voltage would be removed from the tube under test and the rectifier capacitors discharged and grounded when the area was entered. This made it possible to change tubes in the tube test stand without removing the filament voltage from the rectifier tubes of the main power supply.

The rectifier and control-cabinet area could be entered only from the tube test-stand area through a gate having an interlock contact, which deenergized all circuits of the tube test set with the exception of the control-power transformers.

The filament transformer located at the tube test position was rated 3 phase, 60 cycles, 4.65 kva, 805/22.1-12.7 volts line to neutral. The water-flow indicator that was supplied at this position was a venturi type with interlock contacts that were adjusted to assure a minimum water flow of 10 to 15 gal per minute through the tube under test. There was also mounted on the tube test stand a discharge switch similar to that used in the high-voltage cubicle. This switch was used to discharge and ground the rectifier filter capacitor automatically.

At the tube test stand an indicator was provided for determining the number of gas kicks that occurred during the time the tube was under test. This gas-kick counter was connected across a resistor placed in series with the tube under test. When a gas kick occurred, the voltage drop of the series resistor would increase to a value sufficient to break down a spark gap in the gas-kick counter, thus causing current to flow through the gap and through a 35-ohm resistor in series with it. The voltage developed across this second resistor was utilized to operate a mechanical counter. This gas-kick counter was later replaced by CEW-TEC with a thyratron-controlled solenoid-operated counter, which allowed the counter register to be placed on the operator's control panel for greater convenience.

In the operation of the tube test set, when the control-power circuit was energized, the main-line contactor closed and supplied 460 volts to the bus of the test set. The induction voltage regulators used for control of the rectifier-tube filaments and the filament of the tube under test were automatically returned to their minimum voltage position. At the minimum voltage position the filament-supply contactors were closed, and the induction voltage regulators automatically increased the filament voltages to a preset value. The rectifier-tube filaments were preset at normal operating voltage, but the voltage of the tube under test was adjusted to approximately 50 per cent of its nominal value, the final adjustment being made by manual control of the induction voltage regulator.

After the filament time-delay relay had timed out, the grounding switch was energized, removing the short circuit and ground from the rectifier filter capacitor. Plate voltage could then be applied to the tube under test, this voltage being adjusted by manual operation of an induction voltage regulator to the value specified in the tube test procedure. The plate voltage to the tube under test was controlled by an automatic timing cycle in such a manner that this voltage was applied for a period of 2 sec after a rest period of 6 sec. This cycle of 6 sec off and 2 sec on was repeated as long as the plate-voltage control switch was in the operating position. During the time that the control was in the operating position and plate voltage was applied to the tube, the plate current of this tube was indicated by means of an ammeter mounted on the operator's control panel. The number of gas kicks occurring during this period was determined by the difference in the readings of the gas-kick counter before and after the test period.

In September 1944 the outline of a procedure was issued which set forth the routine and responsibility of testing and handling electronic tubes. All tubes were subjected to as complete an acceptance test as possible with existing equipment within 10 days. If a tube failed to pass the test, it was returned to the manufacturer for adjustment.

Because these tubes operated at nearly maximum ratings, General Electric insisted that the tubes installed in one rectifier have the same emission characteristics. Consequently all radiation-cooled rectifier tubes that passed the acceptance test were classified and identified according to the following classes: plus 3, plus 2, plus 1, 0, minus 1, minus 2, minus 3, etc. These classes represented the voltage deviation from the standard filament voltage as read on the filament voltmeter of the emission test set, and thus the tubes were classified in groups according to their emission characteristics. However, by Sept. 1, 1944, CEW-TEC experience had shown that the number of classifications could be reduced, and a new procedure was set up whereby all radiation-cooled rectifier tubes were classified according to groups X, Y, and Z. These groups contained the previous classes of tubes as follows: Group X contained class 0 and all plus tubes; group Y contained minus 1, minus 2, and minus 3 tubes; group Z contained all remaining minus-class tubes.

After the radiation-rectifier tubes had been classified as described above, they were next tested for gas by the inverse-voltage test set that has previously been described. All the radiation-cooled rectifier tubes with the exception of the KC4-A and KC4-3 types were operated at normal filament voltage and at an inverse peak voltage of 165 kv in this test set for a period of 2 min. At the end of the 2-min period the inverse voltage was reduced to 150 kv and the tube was operated for

a period of 5 min, during which period the number of gas kicks that occurred were recorded. Tube types WL-616, WL-619, GL-681, and KC-4 were considered acceptable for service if, during the 5-min period when 150 kv inverse peak voltage was applied, no more than five gas kicks occurred. The ML-100 and ML-200 tubes, because of the type of service to which they were subjected, were considered acceptable if, during the 5-min period when 150 kv inverse peak voltage was applied, no more than two gas kicks occurred.

The KC4-A and KC4-3 tubes were initially subjected to 125 kv inverse peak voltage for a period of 2 min. This voltage was then reduced to 100 kv, and the tubes were operated at this value for a period of 5 min. These tubes were considered acceptable for service if the number of gas kicks recorded during this 5-min period of 100-kv operation did not exceed five.

The water-cooled rectifier tubes were given an initial inspection when received, which included checking for defects in the envelope, element support, anode indentation, etc. These tubes were also inspected for and a check made of filament continuity and any shorts that might exist between elements. Rectifier tubes that passed this initial inspection were then given a gas test by the water-cooled-tube test set described above. These tubes were placed in a tube test set and operated at a filament voltage that was adjusted to give a plate current of 500 ma for a plate voltage of 40 kv. Under this load condition the tube was operated for a period of 7 min. During the first 2 min of this test no check was made of the number of gas kicks that occurred. The tube was considered acceptable for operation if no gas kicks occurred during the next 5 min of the test. Another test was made under the same load condition for an additional 5 min, allowing the tube a chance to clean up. If during the second 5-min test period no gas kicks were recorded, the tube was considered acceptable. If the tube failed to clean up during the second 5-min test period, it was considered to be a gassy tube and was so marked.

Questionable tubes removed from rectifier service were sent to the tube test department for retest. The retest procedure was identical with the initial test procedure as described above, and if the tube was found to be good, it was sent back to stock. However, if the retest tube was found not to be serviceable, this tube became salvage. The flow chart shown in Fig. 5.28 illustrates the method by which new tubes and retest tubes were handled within the plant between the various production buildings and the tube test department.

As has been noted in the previous discussion, a considerable number of protective overload relays were in service in the plant, and because these relays did not maintain their calibration, it became essential to have some means for checking and calibrating these relays. At the

start of plant operation in Alpha I this test equipment consisted of a variable load, timer, ammeter, and disconnect switch. The equipment was mounted in a compact box in order that it could be easily moved to the relay location in the high-voltage cubicle. When the Alpha I relays were converted to the drawout type, this equipment was set up on a permanent test table. Similar equipment was used for checking the Alpha II drawout relays.

The final relay tester adopted in the Beta plant consisted of a 115-volt source of supply, a Variac used as an adjustment means, and a 2 to 1 transformer to step the Variac output voltage down to the desired value. A resistor having approximately 40 times the resistance of the relay coil was inserted in series with the relay coil and ammeter, the combination being connected to the secondary of this transformer. A shorting switch was provided across the relay coil in order to apply full current to the relay instantaneously when the time-delay element was checked. The relay to be tested was inserted in suitable jacks of the relay tester, the power was turned on, and adjustment was made by means of the Variac until the desired test current was obtained. The shorting switch was then closed across the relay coil. Opening the shorting switch applied full current instantaneously to the relay with a very small change in current resulting from this switching operation and with transients being negligible. This type of checker proved very desirable because it eliminated the necessity of a large load box and also preserved good wave form during switching.

Relay checkers were supplied for each of the operating buildings, and checks of all overload relays were made every 30 days in order to maintain the maximum protection for the high-voltage equipment.

The relays were set with an allowable tolerance of ±2 per cent of the desired current value. The current value at which they were set was in a constant state of change because the operating load was increasing gradually and because the relays were being utilized to give maximum protection to both the high-voltage rectifier equipment and the tank load. In Alpha I equipment the load increased to the point where the final relay settings were such that the rectifier equipment operated at 100 per cent of rated value. The relay tripped after 1 to 2 sec at 150 per cent of rating. The Alpha II relays were set so that the rectifier equipment would operate at 125 per cent of rectifier nameplate rating. They tripped after 1 to 2 sec of loads 50 per cent higher. In Beta the load was always the maximum to which process equipment could be subjected and still maintain operation. Consequently it was necessary to provide protection for small overloads and at the same time to provide continuity of operation. This required that the high-voltage-supply overload relays be coordinated with the cubicle-supply relays. In addition an attempt was made to coordinate this with [illegible]ir

circuit breakers at the unit substation that supplied two channels. Actual values of relay settings for a Beta cubicle will serve as a typical example of relay settings in the plant. Beta relay settings were as follows:

Since the normal operation current for the Beta accell was between 150 and 200 ma, the instantaneous relays were set at 600 ma direct current. This corresponded to 8.65 amp alternating current on the secondary side of the current transformer, whose ratio was 3.5 to 1.

The time delay was set to hold 250 ma direct current corresponding to 3.67 amp alternating current. The selector plug was in the 3-amp position for this setting, and the time lever was set on the No. 10 position for greatest time delay. The term "set to hold 250 ma direct current" means that the relay was adjusted with the time-lever setting on No. 10 position so that with the corresponding 3.67-amp alternating current the disk would rotate to the point where the contacts were just ready to close. Any small additional increment of current would then close the contacts, tripping the contactors and clearing the faults.

The decell rectifier required two settings, one for normal or run current and one for the lower value during the bake-out period. The following settings are typical:

For bake-out the instantaneous adjustment was set for 1,400 ma direct current, corresponding to 7.3 amp alternating current on the secondary of the current transformer, whose ratio was 10 to 1. The time-delay setting was set to hold at 450 ma direct current, corresponding to 2.35 amp alternating current. The selector plug was placed in the 2.0-amp position, and the time lever was set on No. 10 position.

With the relays set in this manner, when the bake-out switch was returned to the normal or run position, resistors were shunted across the relay coil to give the following values: instantaneous setting of 1,800 ma direct current ±10 per cent, corresponding to 9.3 amp alternating current ±10 per cent. The time delay was set to hold at 700 ma direct current ±10 per cent, corresponding to 3.62 amp alternating current ±10 per cent. A tolerance of 10 per cent was allowed owing to the tolerance of the shunting resistors. The main-cubicle overload relays were set for a relay coil setting of 5 amp alternating current and a time setting on No. 10. Since the current transformer ratio was 30 to 1, this was equivalent to a primary current of 150 amp alternating current.

The overload settings for the 460-volt air circuit breakers, which supplied two cubicles, were as follows: The instantaneous-trip attachment was set to trip at approximately 4,500 amp, and the time delay was set to trip at 450 amp, minimum time. These settings were later changed so that the time delay would trip at 600 amp, half time.

As an explanation of the differential between the instantaneous and time-delay settings of the high-voltage-supply overload relays the following should be borne in mind: If the emission limit of the limiter tube in the accell supply and the regulator tube in the decell supply were set at approximately one and one-half times the normal operating current, the time-delay relay would protect against overcurrent or faults at the load. Since the instantaneous setting was above this emission-limiting value, these relays would not operate on load faults but were used for protection of the rectifier and its associate equipment. Coordination curves for Alpha I, Alpha II, and Beta that show the relations between the IAC, PAC, and ACB (air circuit breaker) curves are included in Chap. 6, Sec. 12.

Another piece of specialized maintenance equipment known as the "cable-fault finder" was developed for use in the Alpha II plant. It was developed to determine quickly which of the many high-voltage cables connected to an Alpha II cubicle had failed. Prior to the development of the cable-fault finder, it was necessary to disconnect all the cables in order to isolate the particular cable in which a fault had developed between the high-voltage conductor and the ground sheath. The cable-fault finder consisted of a 1,400-volt a-c supply, which could be connected from the high-voltage conductor to ground. A special clip-on coil in conjunction with a suitable amplifier and ammeter was then used to determine which of the cables of the particular channel was passing current from the high-voltage conductor to ground.

As has previously been stated, maintenance was a major problem during the operation of the high-voltage equipment, and in this respect the elimination of dust and dirt from the equipment was a serious problem. Why this was true can more readily be seen from a summary of conditions that existed at the plant site during operation.

The CEW-TEC plant was located in a valley and included two steam plants that utilized soft coal as fuel for stoker-fired boilers. Since these steam plants utilized neither fuel savers nor smoke filters, a great deal of soft-coal smoke and soot settled into the valley. In addition a considerable number of coal-fired railroad engines without smoke filters were operated around the operating buildings. The first year and a half of plant operation occurred during the period when hard-surface roads did not exist in the plant-site area. Since the roads were subjected to a great deal of heavy travel and since rains occurred frequently, the dust and mud existing in this area was considerable. Considering all the above facts it is readily realized that very many dirt and smoke particles existed in the air.

The operating buildings, as designed and built by Stone & Webster, included filtered-air chambers into which air was drawn from the outside through filters by means of suction fans. However, although large objects could not pass the filters, a great many dust and smoke particles were drawn into the air chambers. From these air chambers air was blown into the high-voltage cubicles, and as the dirt particles entered these cubicles, they became charged and were attracted to the high-voltage insulators, conductors, and other pieces of equipment. This eventually resulted in either a conductor breakdown or a bushing flashover. To minimize such failures a maintenance procedure was put into effect which required that at each interrun period the high-voltage cubicles were to be cleaned. This meant that each insulator and other circuit component had to be wiped with a clean rag to remove this dirt. The construction of the high-voltage cubicle was such that it was difficult to gain access to some of the parts, and consequently such a cleaning job was a dirty one and unwanted. A considerable number of proposals were made to remedy this condition. However, the pressure of other problems during the war prevented any effective remedy, and the effects of dirt were tolerated generally, despite their demoralizing influence on maintenance personnel. The accumulation of dirt on contactors and relays during a production run was often great enough to cause these components to cease to function during the run. This resulted in lost production time because it was necessary to stop other operations in order to clean the contacts of these items.

Added to the problem of dirt was the crowding of equipment in the high-voltage cubicle, making it practically impossible to gain access to some portions of the equipment even for routine maintenance. It became desirable in some cases to operate the equipment without repair since damage to surrounding equipment occasioned while gaining access to the equipment to be repaired would outweigh the benefits of the repairs.

Consequently, in order to ensure continuity of operation and to gain the best possible service from the equipment under the severe operating conditions, a comprehensive preventive-maintenance program was set up as a standard procedure. The interrun period between process runs was of such short duration that it was impractical to conduct all the preventive-maintenance work that was required owing to the conditions at the plant site. Therefore the inspections were broken up into three groups, one at each run termination and the other two at 60-day and 12-month intervals, respectively.

The inspection at each run termination included such items as the inspection of grounding hooks and grounding-hook cables for safety,

the checking of grounding relays for mechanical operation, the checking of the water-flow interlocks for operation, the checking of the door and safety interlocks, visual inspection of the protective-relay contacts, the inspection of the contactors and control relays for mechanical operation and service, and the removal of dust from the rectifier tubes, high-voltage insulators, Lapp coil, meter faces, and cubicle windows.

The 30-day inspection included, in addition to the termination checks given above, such items as calibration of the protective relays, a general cleanup of the high-voltage cubicle and equipment, utilizing both rags and vacuum cleaner to remove the dirt and dust, and a thorough inspection of the contactors and relays. The 30-day inspection also included the calibration of the protective relays and the checking of the filament voltage of the rectifier, regulator, and limiter tubes.

The 12-month inspection included such items as the blowing out of the motors and induction voltage-regulator windings with compressed air, the greasing of the induction voltage regulators and motor bearings and control gearing, the taking of oil samples from the rectifier transformers and voltage dividers and the filtering of this oil when necessary, a thorough contactor and relay inspection and repair, and a thorough removal of dust and dirt from all the equipment. Figure 5.29 is a sample of a typical channel-termination check sheet, and Fig. 5.30 is a channel electrical inspection and maintenance check sheet.

When failure of any of the electrical equipment occurred during regular plant operation, it was required that the Process Department make a request, on a trouble-report form, to the Electrical Department before the piece of electrical equipment in question would be repaired. These trouble-report forms included four major items of interest: (1) nature of the trouble, (2) how corrected, (3) repair time, and (4) outage time. A typical form is shown in Fig. 5.31. These forms were collected and sorted according to the type of trouble and amount of repair time and outage time, and a record of the number of defects of each particular type was kept. From these trouble records it was possible to determine what type of failure was occurring most often, the time required for repair, and the amount of time lost from production.

The information was used to determine whether it was advisable to redesign or modify some of the equipment in order to reduce loss of production time. Lost production time could be compared with the time that would be required to make equipment modification, and from this study a relative evaluation could be made. From such studies a great many cases were found where the frequency of failures and the

repair time and cost required by such failures justified a change that would pay for itself after a very short period.

Time studies were also made to determine the amount of time required for each type of preventive-maintenance operation, what type of maintenance repair was most essential, and the frequency at which these repairs or inspections should be made in order that the available time would be utilized to the best advantage.

From these time studies maintenance personnel were furnished procedures to follow in making checks, and check sheets were furnished for the tabulation of inspection and repairs so that a complete record could be kept for each production unit. These records were periodically reviewed and revised to meet current conditions so that the maximum benefits in plant operation could be obtained.

Table 5.1 — Summary of Reported Troubles and Equipment Replaced in Alpha I High-voltage Supplies*

Item	Average no. of troubles reported per month	Average no. of items replaced per month	Replacements per month of total number in operation, %
Rectifier high-voltage circuit:			
Wiring troubles	50		
Grounding switches	15	4	0.52
Decell resistors	3	1	0.06
Decell filter capacitors	17	8	0.70
Decell line-termination capacitor			
50 kv — insulated from case for 30 kv	40	40	10.4
50 kv — insulated from case for 50 kv	0	0	0
Accell resistors	58	55	4.76
Accell filter capacitor	2	1	0.26
Metering circuit			
Meters	15	14	0.94
Protective devices	13	11	1.27
Accell rectifier tubes	240	240	20.4
Decell rectifier tubes	800	800	34.8
Limiter and regulator tubes	50	33	4.3
Accell rectifier high-voltage and filament transformers	0.11	0.11	0.03
Decell rectifier high-voltage and filament transformers	0.33	0.33	0.09
Supply and control circuits:			
Wiring troubles	20		
Induction regulators	20	5	0.26
Limiter and regulator circuit	40		
Rectifier step-start circuit (before change)	200		
Contactors: 75- and 25-amp main, 50- and 25-amp aux.		150	10.4
Resistors: 2 ohms, 80 watts; 6 ohms, 80 watts		450	26.0
Rectifier step-start circuit (after change)	12		
Contactors: 150-amp main, 75-amp aux.		6	0.75
Resistors: 2 ohms, 180 watts		24	2.04
Relays and miscellaneous contactors:	700		
Protective relays		40	2.6
Main power contactor		0.3	0.78
Miscellaneous contactors and relays		5	0.03
Recyclers	3		

*These data cover 384 high-voltage cubicles for the period January to August 1945.

Table 5.2—Summary of Reported Troubles and Equipment Replaced in Alpha II High-voltage Supplies*

Item	Average no. of troubles reported per month	Average no. of items replaced per month	Replacements per month of total number in operation, %
Rectifier high-voltage circuit:			
Wiring troubles	20.5		
Grounding switches	6	0.25	0.03
Decell resistors	17.3	16.3	0.12
Decell filter capacitors	2.0	2.0	0.52
Decell line-termination capacitor	1.5	1.5	0.39
Accell resistors	0.5	0.5	0.02
Accell filter capacitor	0.5	0.5	0.13
Accell line-termination capacitor	0.25	0.25	0.03
Meters	40	40	2.5
Accell rectifier tubes	400	400	17.4
Decell rectifier tubes	320	320	13.9
Limiter and regulator tubes	80	54	4.7
Accell rectifier high-voltage and filament transformers	0	0	0
Decell rectifier high-voltage and filament transformers	0.02	0.02	0.005
Supply and control circuits:			
Wiring troubles	6.75		
Induction regulators	5.5	2	0.07
Rectifier step-start circuit			
Main contactor	15.25	2	0.52
Auxiliary contactor	26.25	12	3.12
Resistors	10.5	9	2.09
Relays and miscellaneous contactors:			
Protective relays	44	20	1.3
Main power contactor	5.25	2	0.52
Miscellaneous contactors and relays	33.75	13	0.8

*These data cover 384 high-voltage cubicles for the period January to August 1945.

Table 5.3—Summary of Reported Troubles and Equipment Replaced in Beta High-voltage Supplies*

Item	Average no. of troubles reported per month	Average no. of items replaced per month	Replacements per month of total number in operation, %
Rectifier high-voltage circuit:			
Wiring troubles	20		
Grounding switches	4	1	1.39
Decell resistors			
In original location	24	24	33.33
In new location	0	0	0
Decell filter capacitors	2	2	2.78
Decell line-terminating capacitors			
50 kv—insulated from case for 30 kv	25	25	34.8
50 kv—insulated from case for 50 kv	0	0	0
Accell resistors	2	2	2.80
Accell filter capacitors	1	1	1.39
Accell terminating capacitors	2	2	2.78
Metering circuit			
Decell ammeter—resistor in ground side	30	30	41.0
Decell ammeter—resistor removed	1	1	1.39
Other meters	1	1	0.47
Accell rectifier tubes	13	13	6.0
Decell rectifier tubes	48	48	11.1
Limiter and regulator tube	15	8	5.6
Decell high-voltage and filament transformers	2	0	0
Accell high-voltage and filament transformers	3	0.8	0.11
Supply and control circuits:			
Wiring troubles	60		
Induction regulators	3	0.1	0.14
Limiter and regulator circuit	30		
Rectifier step-start circuit (before change)	36		
Contactors: 75- and 75-amp main, 50- and 25-amp aux.		12	8.58
Resistors: 4 ohms, 120 watts; 2 ohms, 120 watts		2	1.43
Rectifier step-start circuit (after change)	10		
Contactors: 150-amp main, 75-amp aux.		0.5	0.35
Resistors: 2 ohms, 120 watts		0	0
Relays and Miscellaneous Contactors:			
Protective relays before wiring change	50	20	6.95
Protective relays after wiring change	0	0	0
Main power contactor	12	0.5	0.69
Miscellaneous contactors and relays	28	1.0	0.04

*These data cover 72 high-voltage cubicles for the period January to August 1945.

Table 5.4 — Maintenance Record of Rectifier Tubes

Process	Tubes in operation Decell	Tubes in operation Accell	Replacements per month Decell	Replacements per month Accell
		Radiation-cooled		
Alpha I	2,304	1,152	800	240
Alpha II		2,880		500
Beta	1,728	864	190	50
		Water-cooled		
Alpha I				
Alpha II	2,880		400	
Beta				

Table 5.5 — Alpha I Tube Costs*

Tube type	Price†	Replacement rate per month‡	No. of tubes per cubicle	Cost per year of original type	Cost per year of final type
General Electric KC-4	$100	120	3 accell	$1,500.00	$1,500.00
General Electric KC-4	100	200	6 decell	2,500.00	1,250.00
Machlett ML-100	100	100			
General Electric GL-893	450	5	1 regulator	281.25	281.25
General Electric GL-562	150	5	1 limiter	93.75	93.75
Total cost per year per cubicle				$4,375.00	$3,125.00
Total cost per year for 384 cubicles				$1,700,000.00	$1,199,900.00

*Based on actual use rate during plant operation.
†Tube cost taken as manufacturer's user's price.
‡For 96 operating channels.

Table 5.6 — Alpha II Tube Costs*

Tube type	Price†	Replacement rate per month‡	No. of tubes per cubicle	Cost per year of original type	Cost per year of final type
General Electric KC-4	$100	100	6 accell	$1,250.00	$1,250.00
General Electric GL-605	150	150	6 decell	2,812.50	1,687.50
Federal F-660	100	90			
General Electric GL-893	450	20	2 regulator	1,125.00	337.50
Machlett ML-503	450	6			
General Electric GL-562	150	1	1 limiter	18.75	18.75
Total cost per year per cubicle				$5,206.25	$3,293.75
Total cost per year for 384 cubicles				$2,690,400.00	$1,266,600.00

*Based on actual use rate during plant operation.
†Tube cost taken as manufacturer's user's price.
‡For 96 operating channels.

Table 5.7—Beta Tube Costs*

Tube type	Price†	Replacement rate per month‡	No. of tubes per cubicle	Cost per year of original type	Cost per year of final type
General Electric KC-4	$100	8	3 accell	$300.00	$300.00
General Electric KC-4	100	50	6 decell	1,750.00	1,125.00
Machlett ML-100	100	30			
General Electric GL-893	450	1	1 regulator	167.50	167.50
General Electric GL-562	150	1	1 limiter	56.25	56.25
Total cost per year per cubicle				$2,273.75	$1,648.75
Total cost per year for 256 cubicles				$582,080.00	$422,080.00

*Based on actual use rate during plant operation.
†Tube cost taken as manufacturer's user's price.
‡For 32 operating channels.

Table 5.8—Characteristics of General Electric Type GL-681 Rectifier Tube

Filament:	
Voltage, volts	20.0
Current, amp	31.5
Maximum rating:	
Peak plate current, amp	1.0
Peak inverse voltage, kv	150
Average plate dissipation, kw	0.45
Momentary overload—maximum time, 3 sec:	
Peak plate current, amp	1.5
Peak inverse voltage, kv	150
Peak forward voltage, kv	3.0
Plate dissipation, kw	0.80
Instantaneous overload—maximum 15 cycles:	
Peak plate current, emission-limited, amp	3.0
Peak inverse voltage, kv	150
Peak forward plate voltage, kv	50

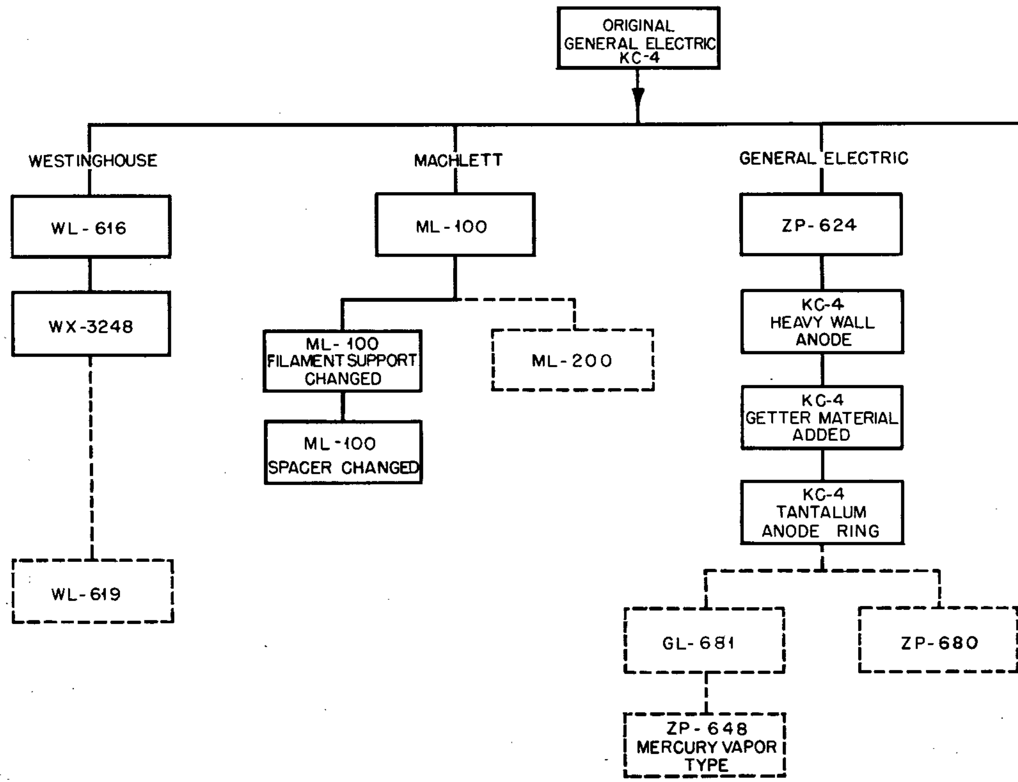


Fig. 5.1—High-voltage air-cooled rectifier-tube development. Solid lines, production tubes. Broken lines, experimental tubes.

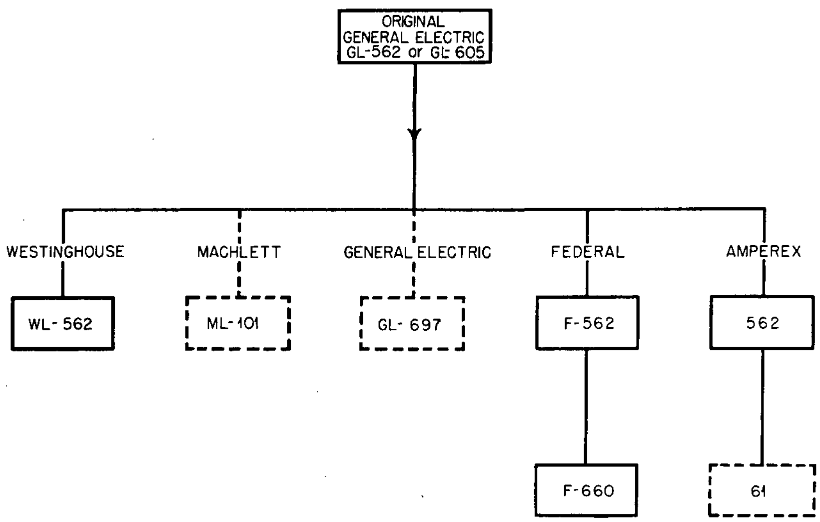


Fig. 5.2—High-voltage water-cooled rectifier- and limiter-tube development. Solid lines, production tubes. Broken lines, experimental tubes.

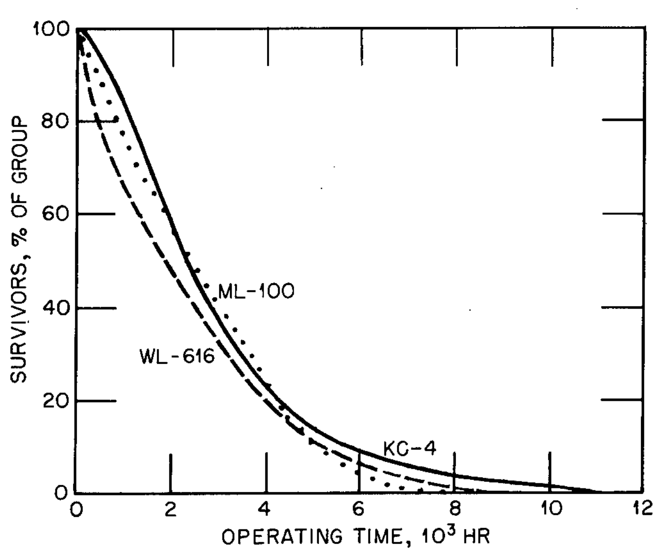


Fig. 5.3—Rectifier-tube survival curve for Alpha I decell-rectifier service. Life expectancy of the tubes is 2,900 hr for General Electric KC-4, 2,600 hr for Machlett ML-100, and 2,400 hr for Westinghouse WL-616.

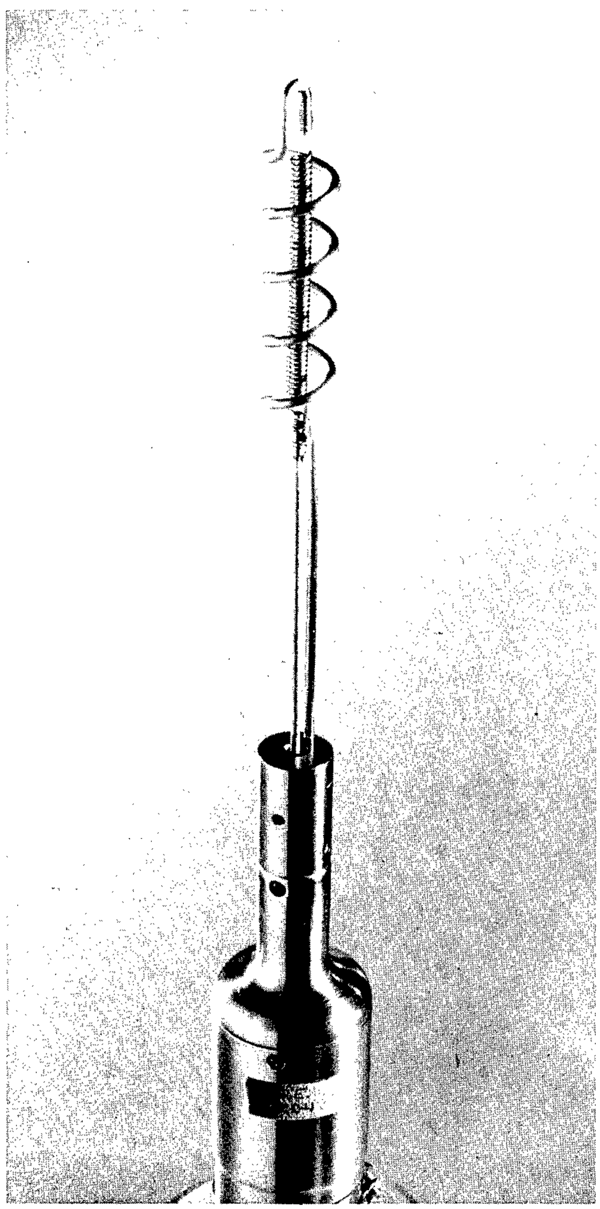


Fig. 5.4 — Filament structure of General Electric KC-4 rectifier tube.

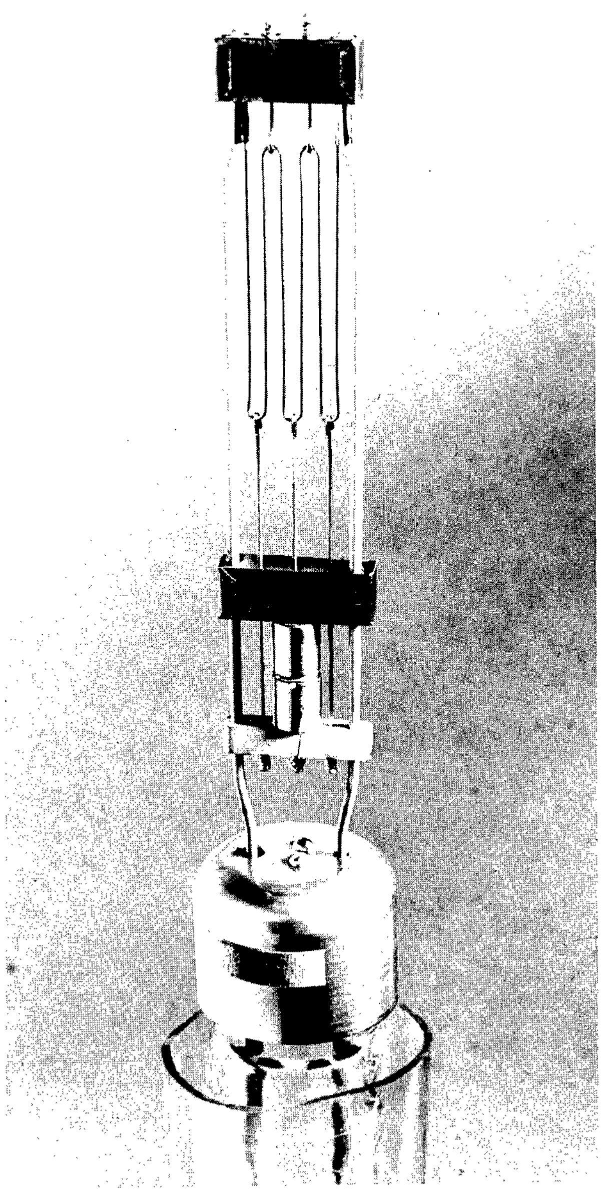


Fig. 5.5 — Filament structure of General Electric GL-681 rectifier tube.

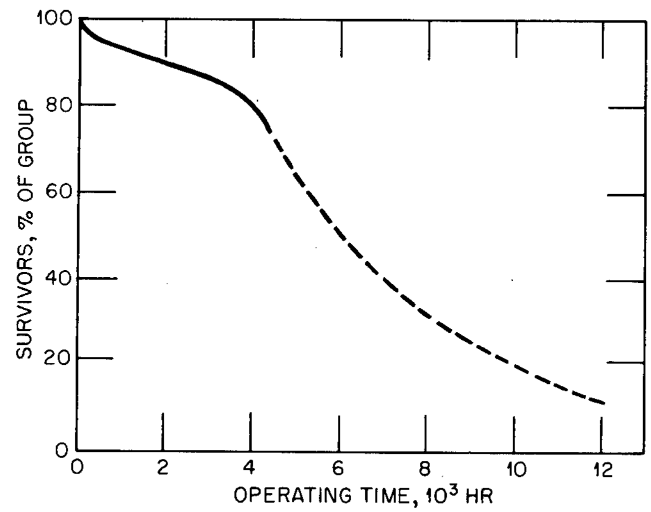


Fig. 5.6—Survival curve for the General Electric ZP-681 rectifier tube in Beta decell-rectifier service. Dashed portion shows predicted future behavior.

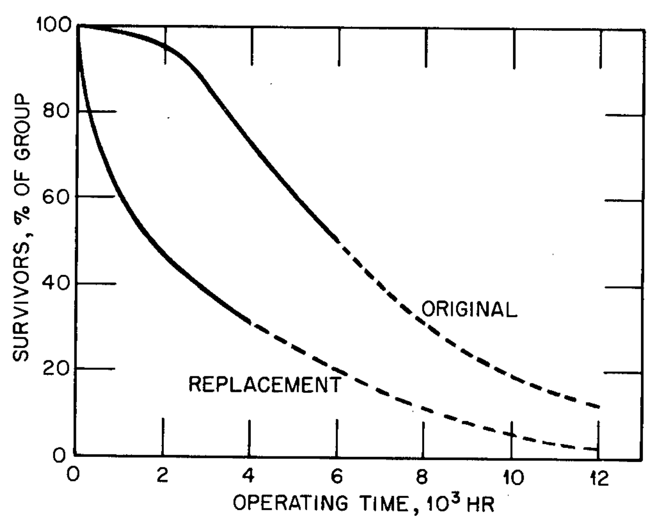


Fig. 5.7—Survival curve for the General Electric KC-4 rectifier tube in Beta decell-rectifier service. Dashed portion shows predicted future behavior.

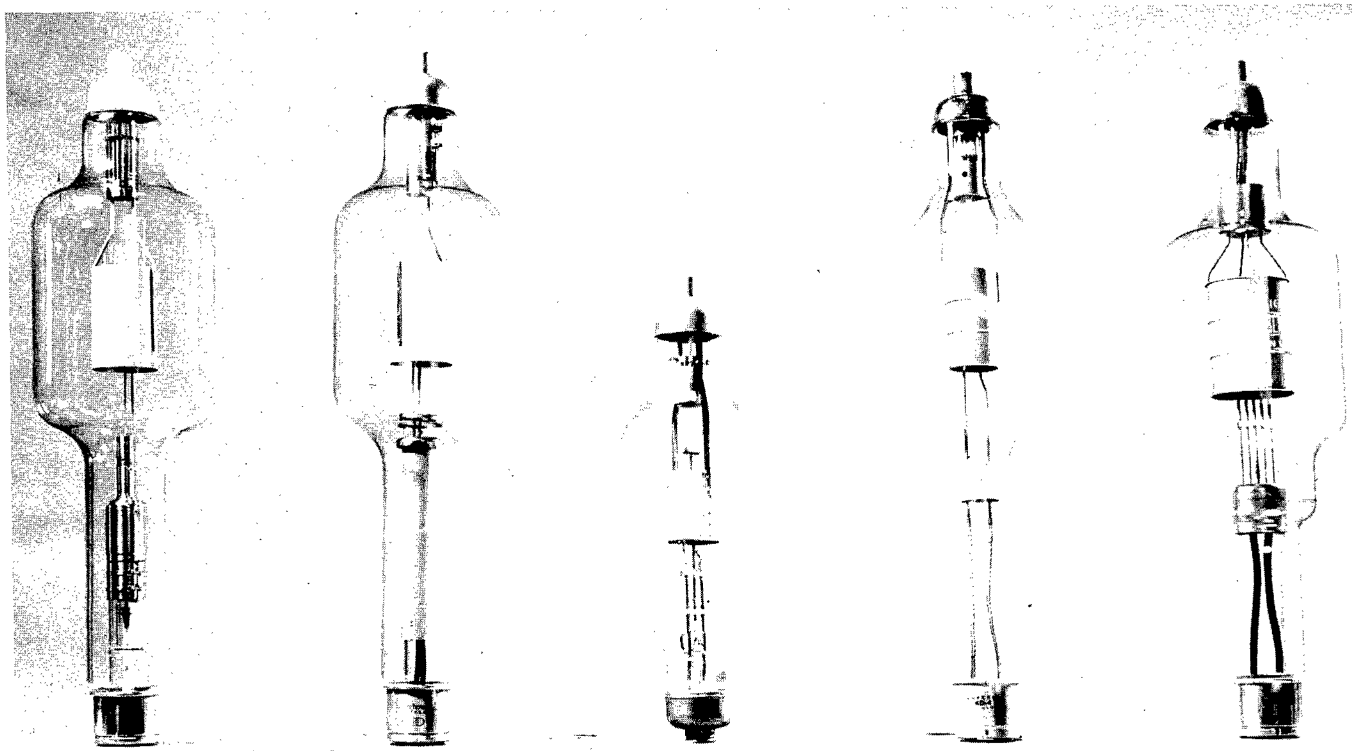


Fig. 5.8—Radiation-cooled rectifier tubes.

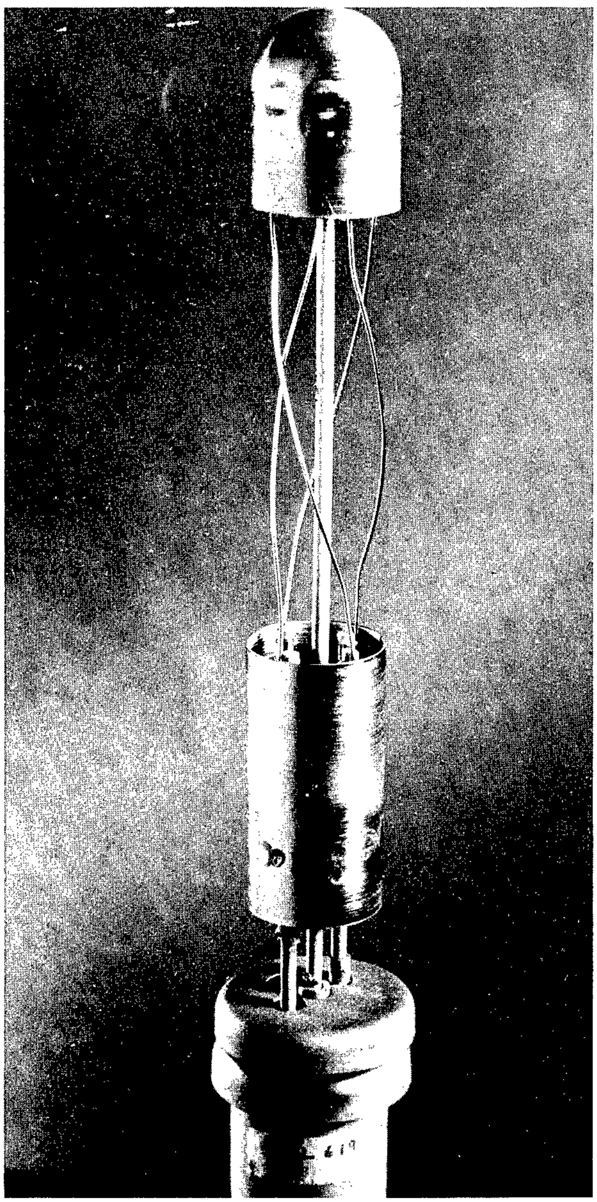


Fig. 5.9 — Filament structure of Westinghouse WL-619 rectifier tube.

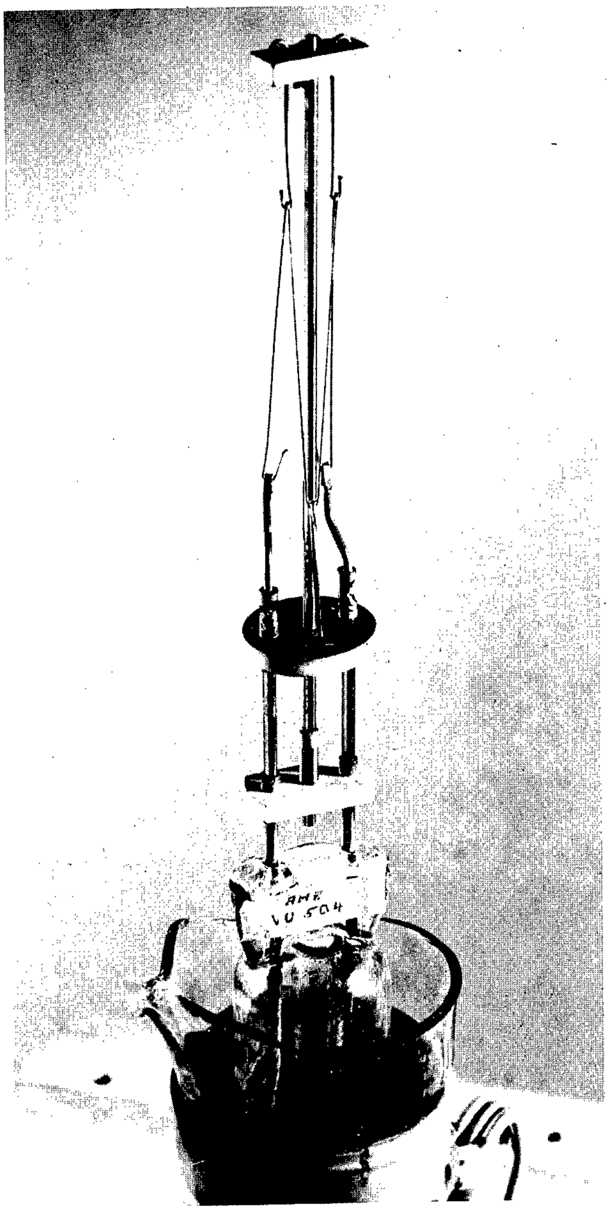


Fig. 5.10—Filament structure of Amperex VU-504 rectifier tube.

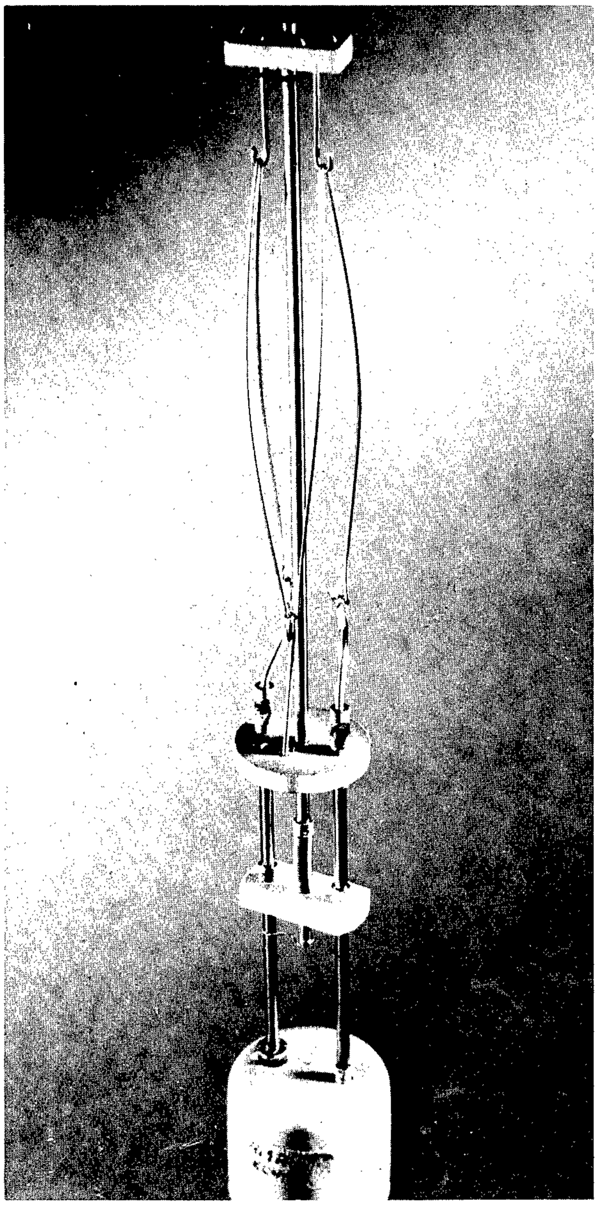


Fig. 5.11 — Filament structure of Amperex KC4-A rectifier tube.

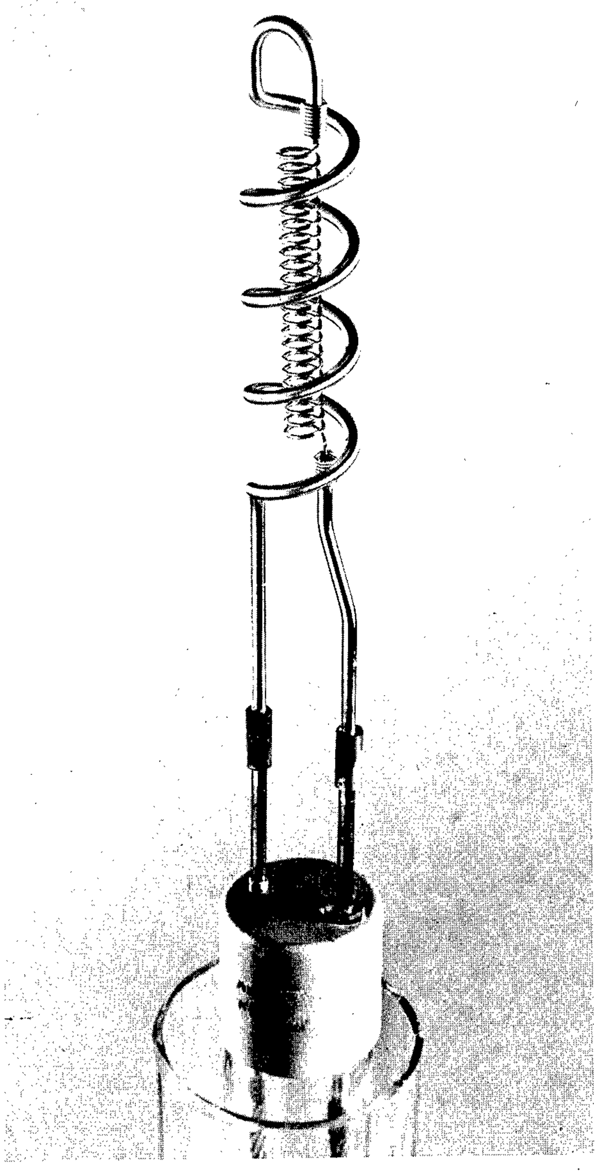


Fig. 5.12 — Filament structure of Amperex KC4-3 rectifier tube.

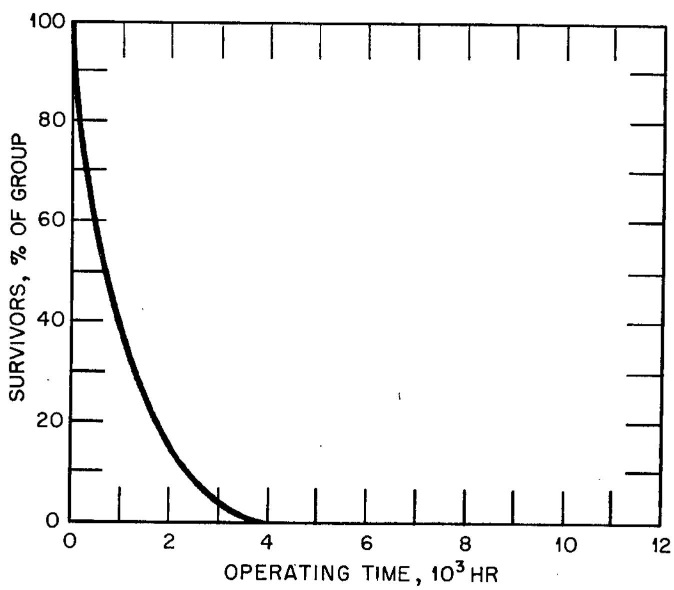


Fig. 5.13—Survival curve for the Amperex KC4-3 rectifier tube in Beta accell service.

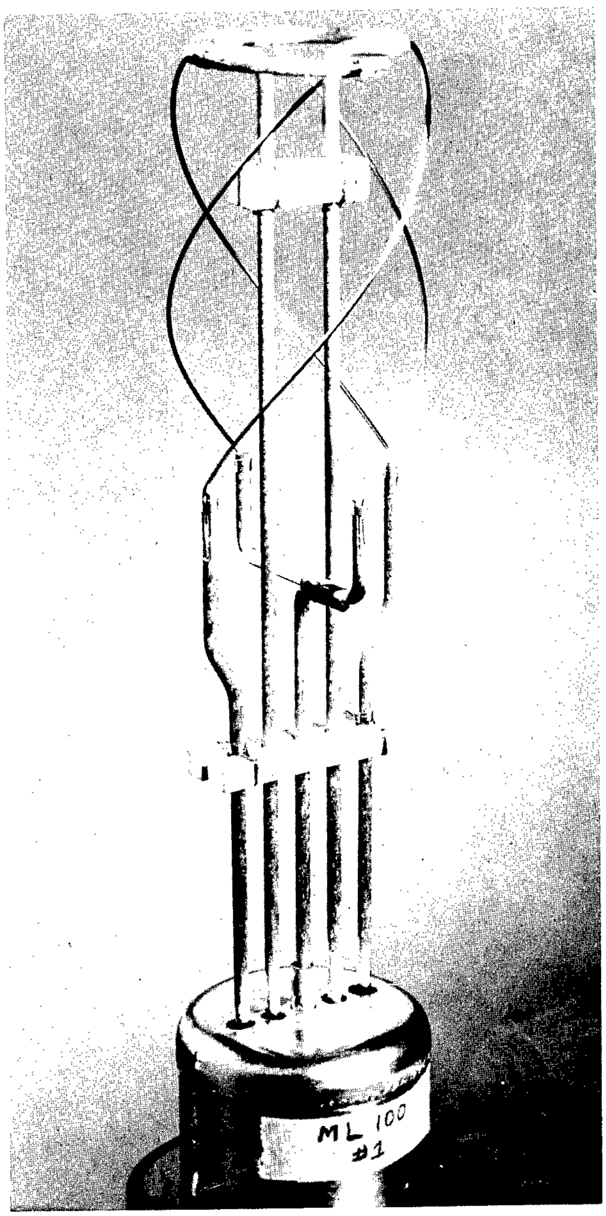


Fig. 5.14 — Original filament structure of Machlett ML-100 rectifier tube.

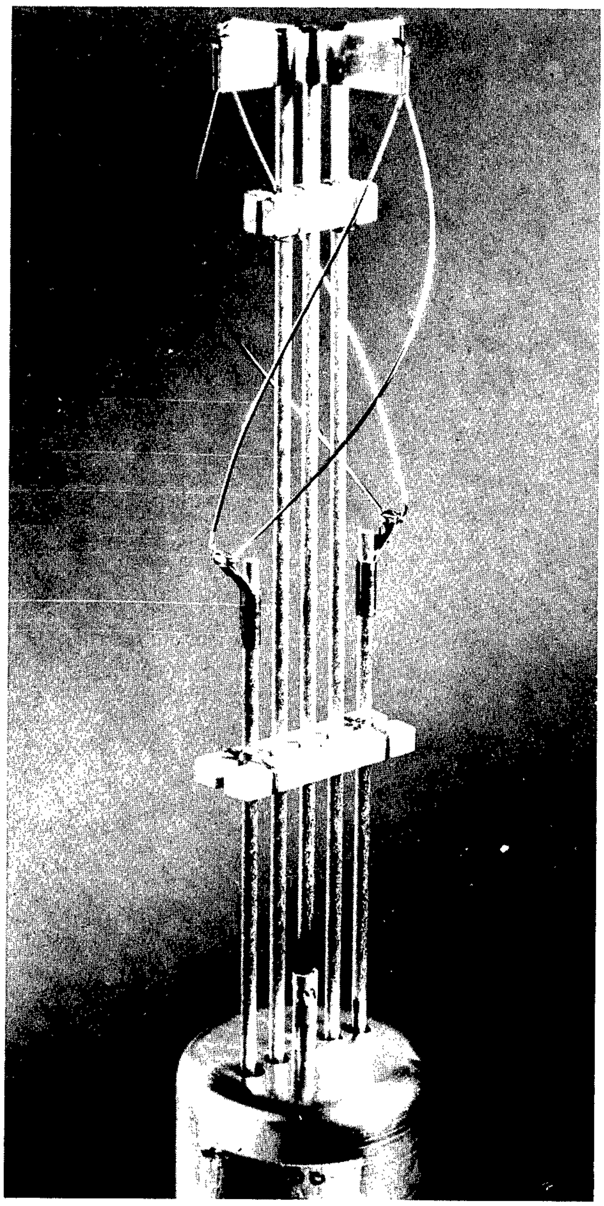


Fig. 5.15—Improved filament structure of Machlett ML-100 rectifier tube.

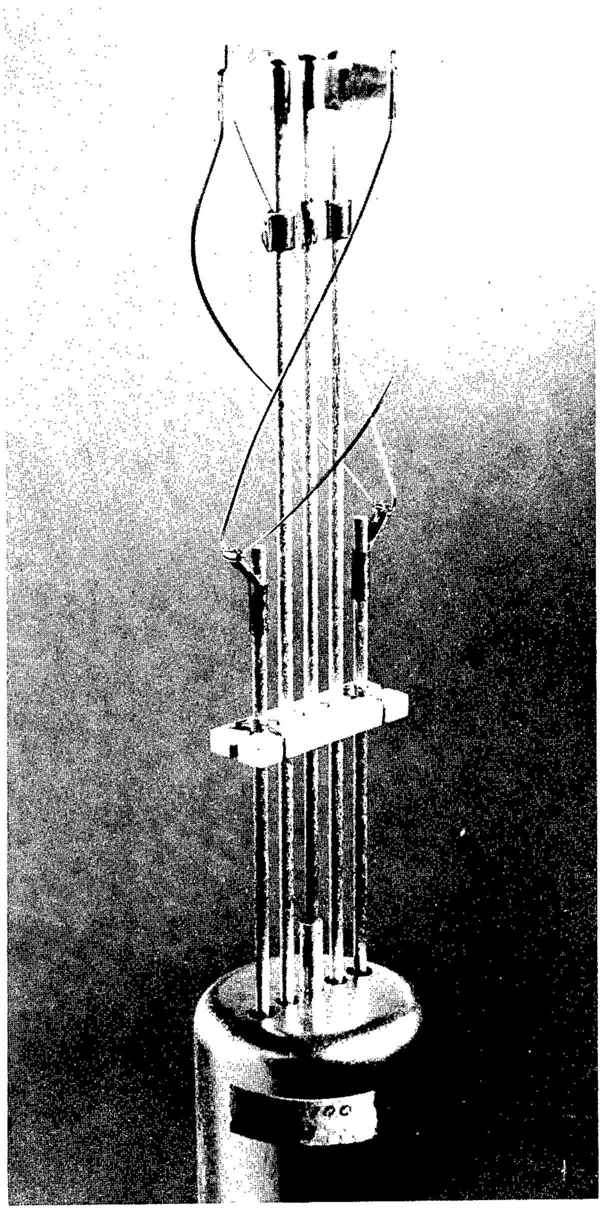


Fig. 5.16 — Final design of filament structure of the Machlett ML-100 rectifier tube.

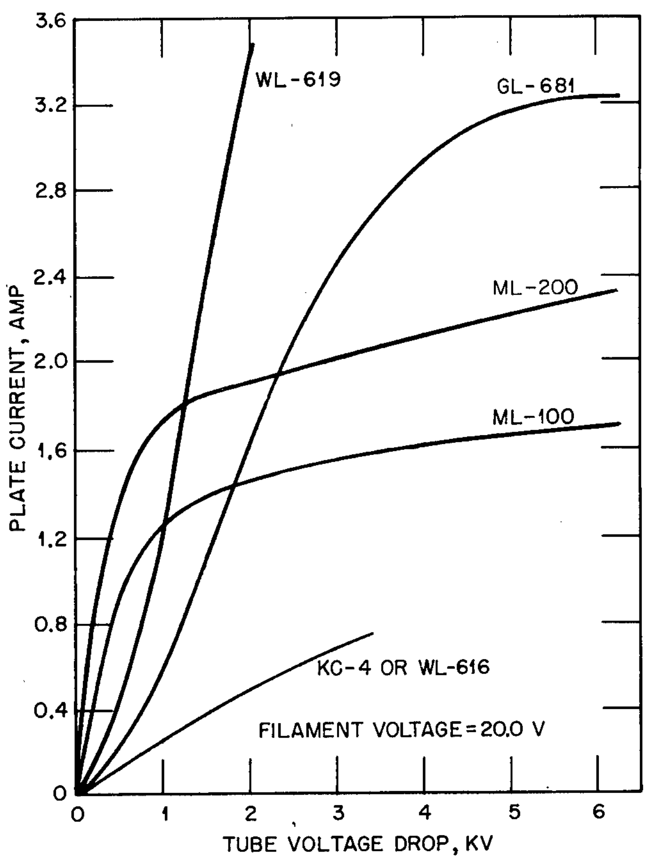


Fig. 5.17 — Plate-current characteristics of radiation-cooled rectifier tubes.

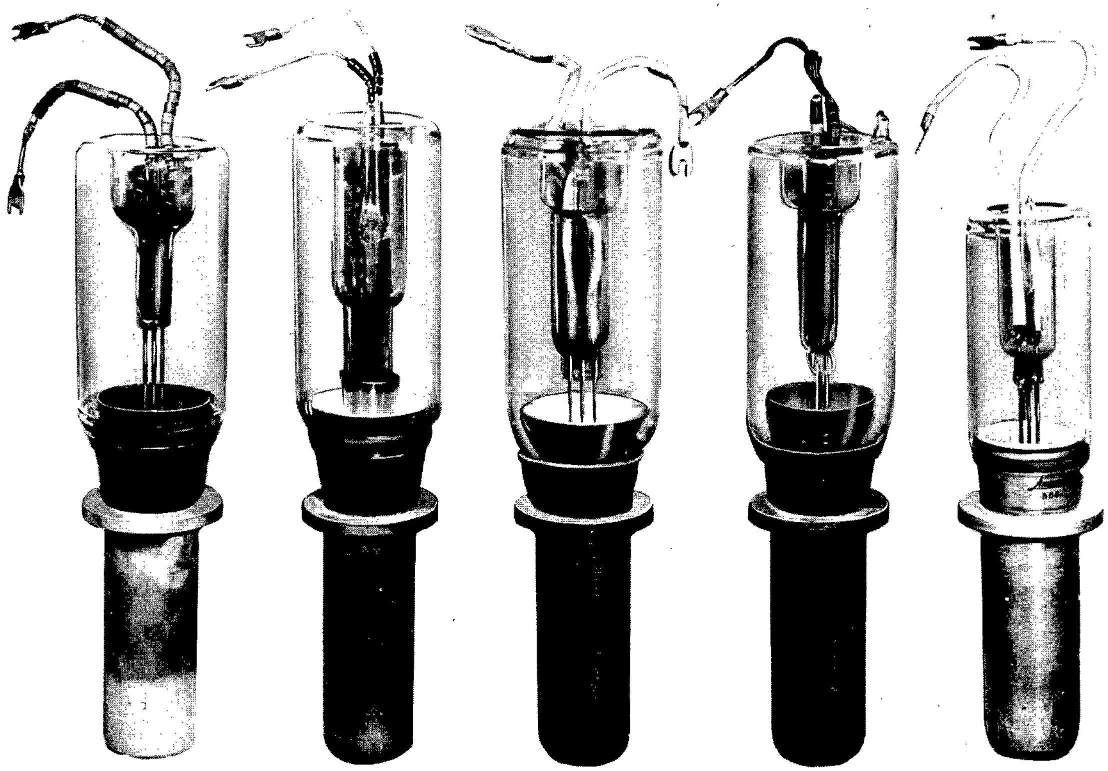


Fig. 5.18 — Water-cooled rectifier tubes.

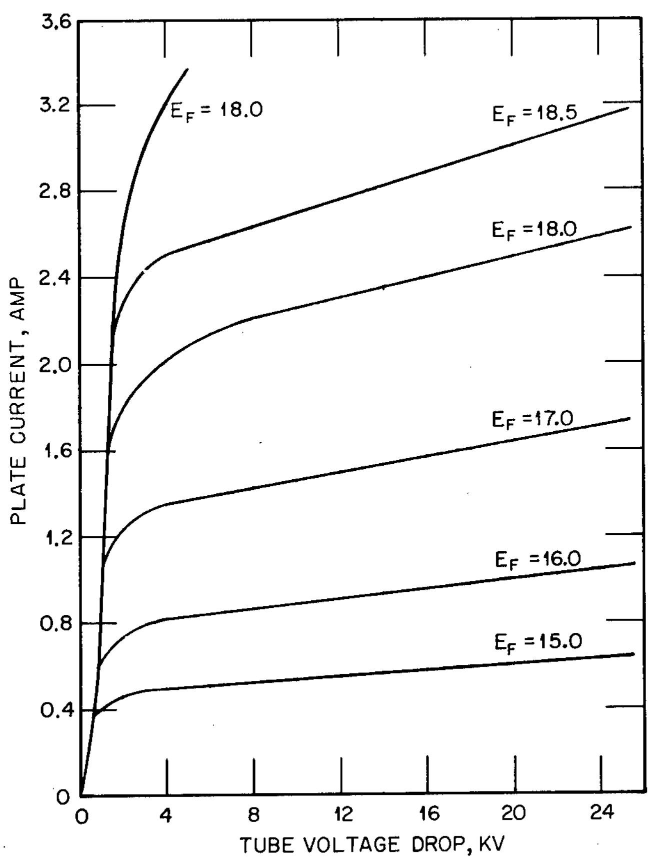


Fig. 5.19—Characteristic curves for General Electric GL-562 rectifier tube. E_F is the filament voltage.

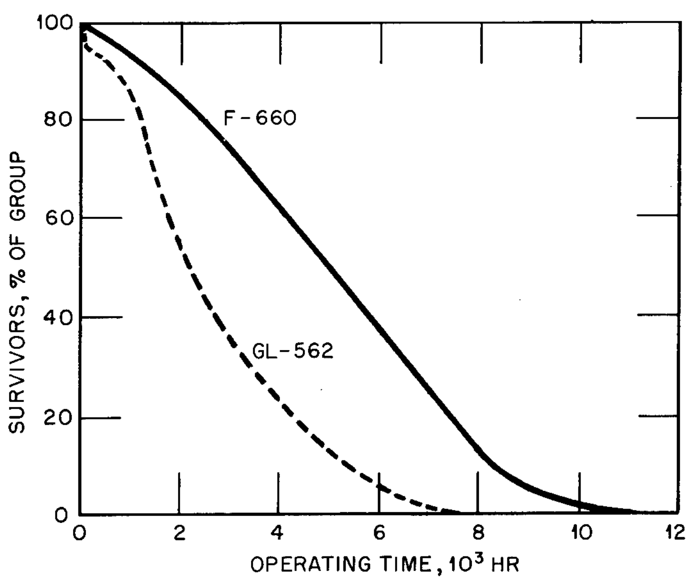


Fig. 5.20—Rectifier-tube survival curve for Alpha II decell-rectifier service. Life expectancy of the tubes is 5,000 hr for Federal Telephone & Radio Corp. F-660 and 3,000 hr for General Electric GL-562.

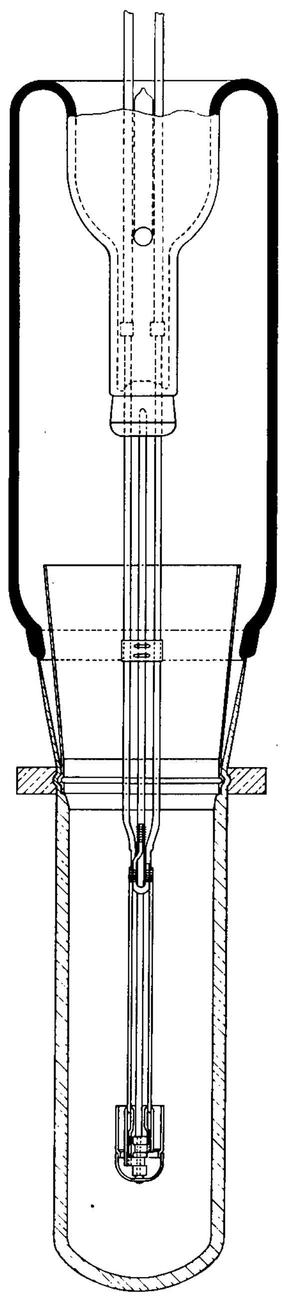


Fig. 5.21 — General Electric GL-697 rectifier-tube filament structure.

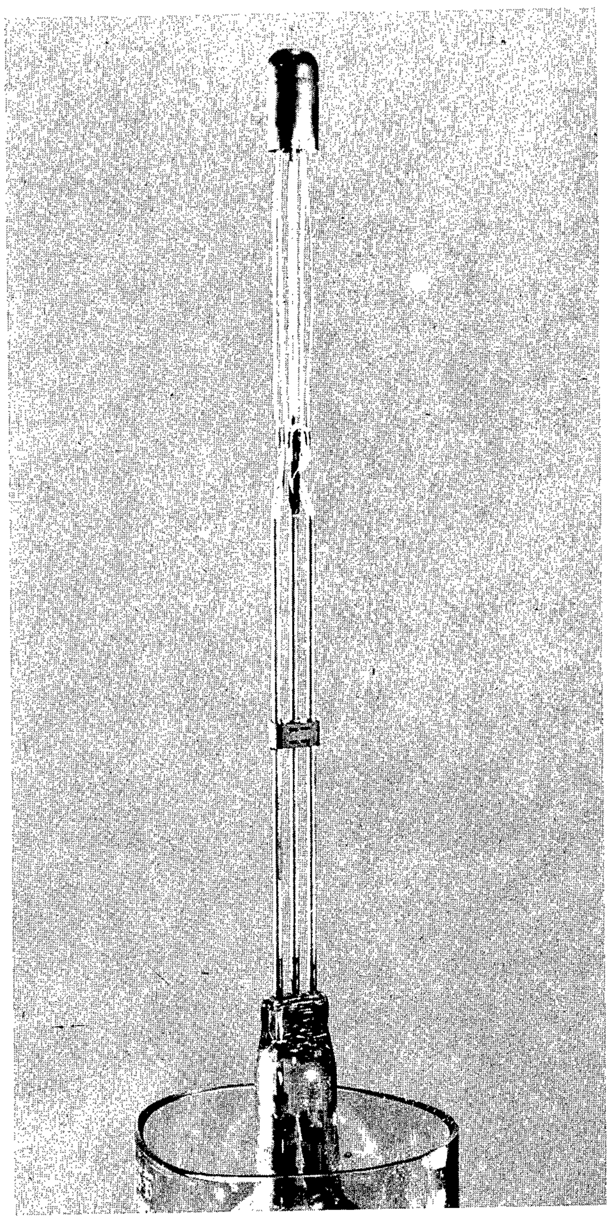


Fig. 5.22 — Filament structure of General Electric GL-605 rectifier tube.

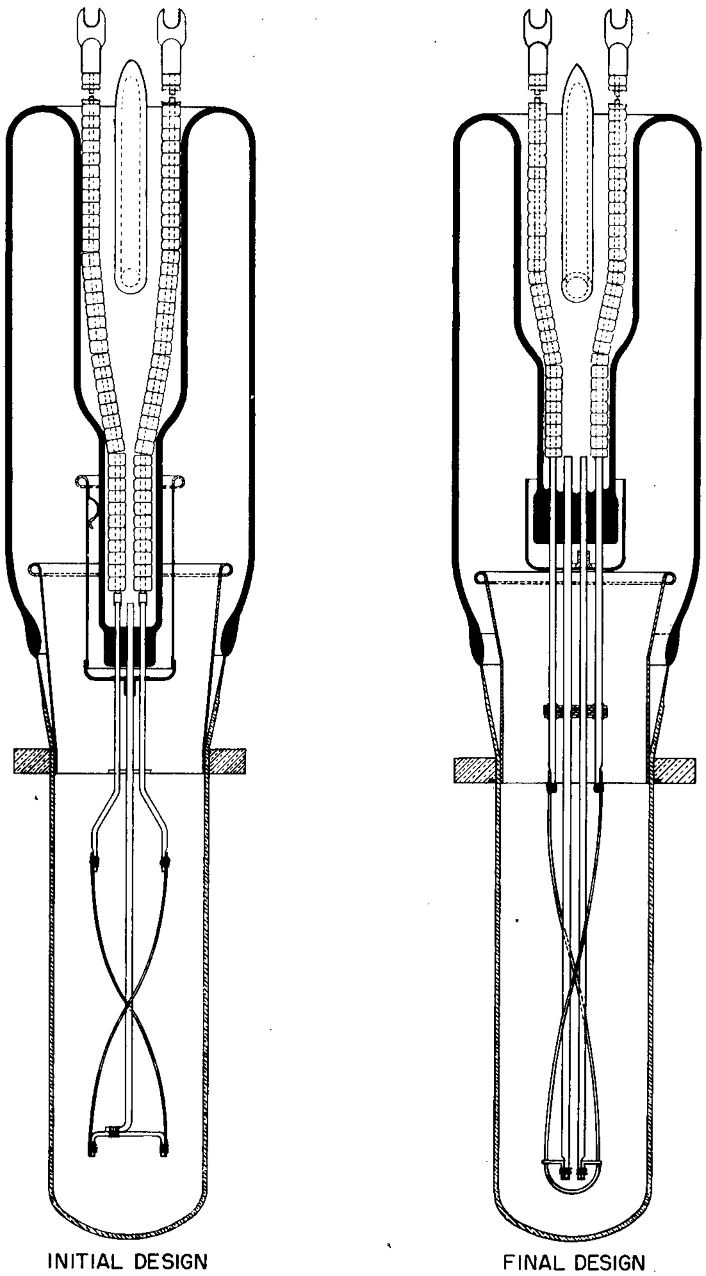


Fig. 5.23 — Filament structure of Machlett ML-101 water-cooled rectifier tube.

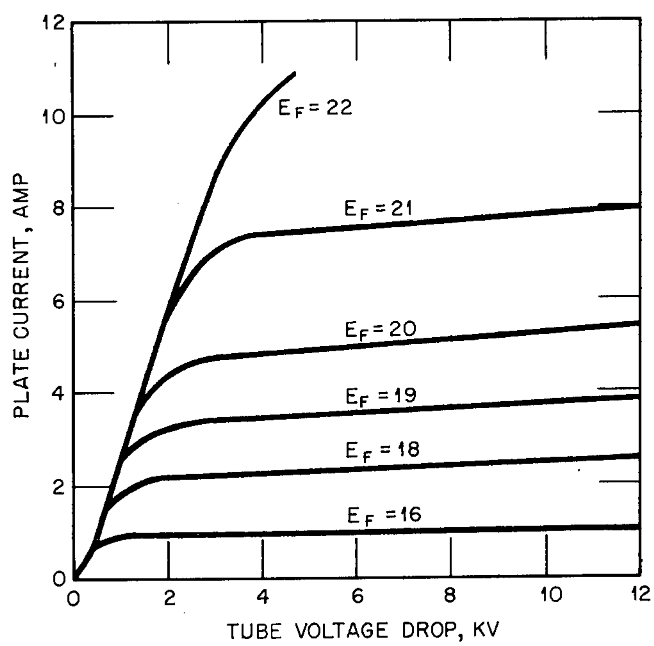


Fig. 5.24—Characteristic curves for the Machlett ML-101 rectifier tube.

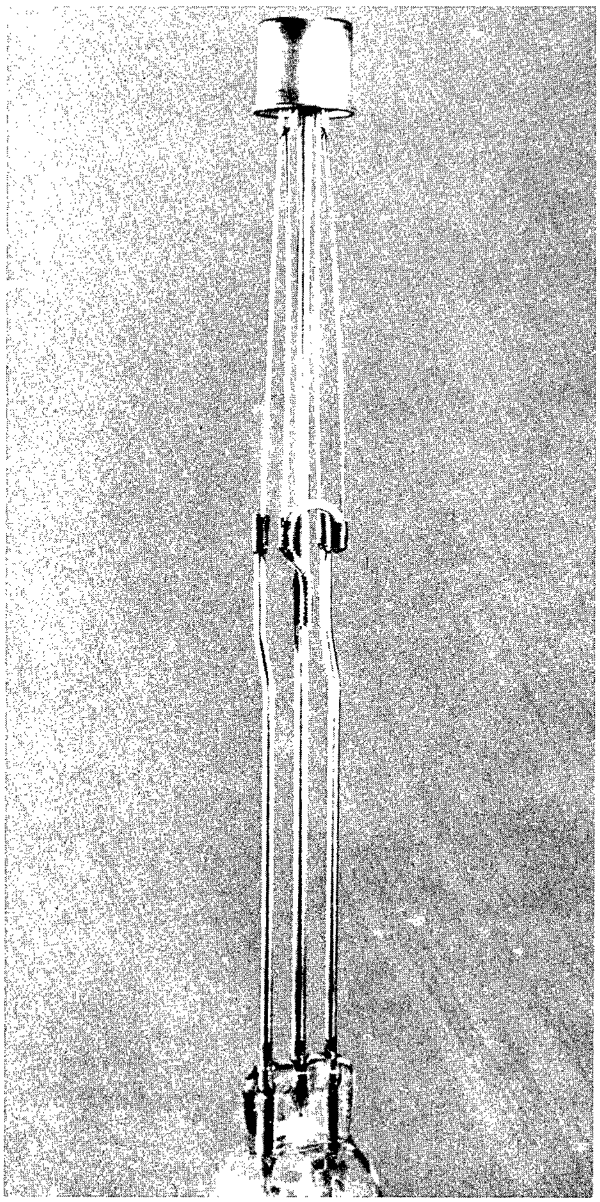


Fig. 5.25 — Filament structure of Amperex 61 rectifier tube.

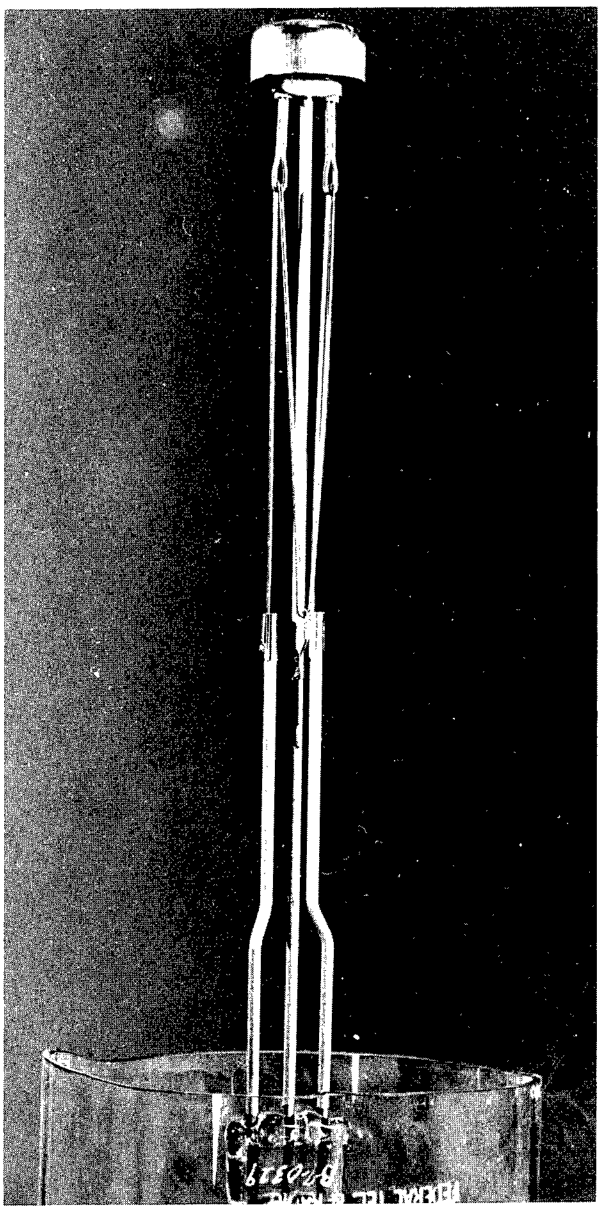


Fig. 5.26 — Filament structure of Federal F-660 rectifier tube.

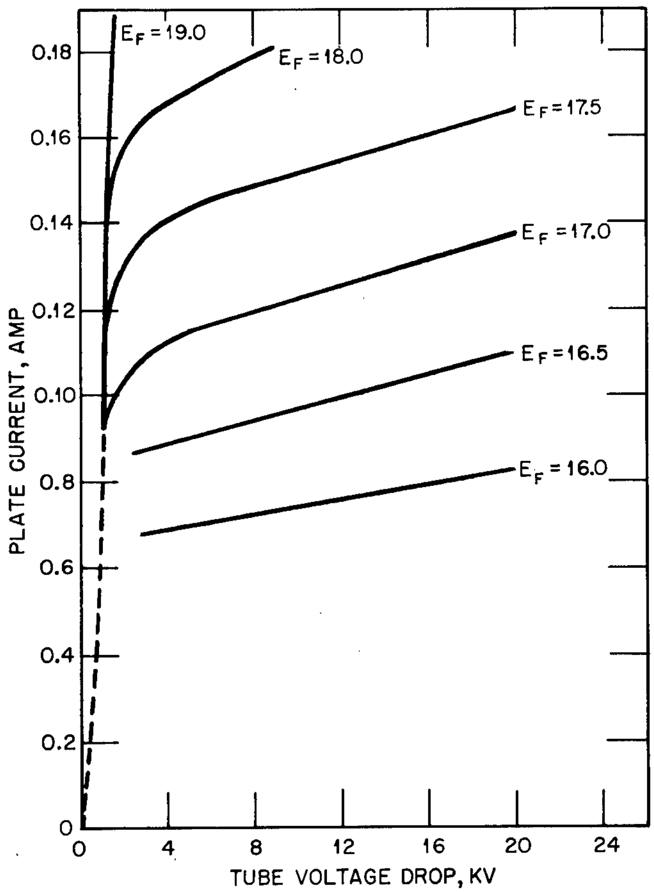


Fig. 5.27—Characteristic curves of the Federal F-660 rectifier tube.

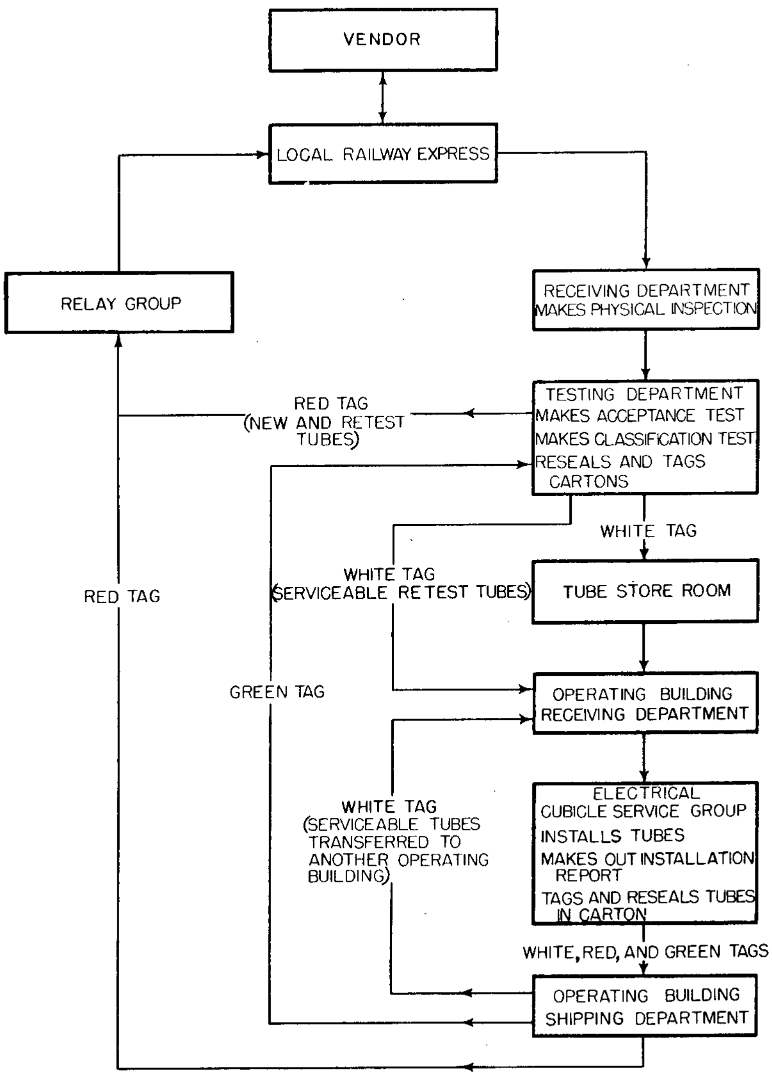


Fig. 5.28—Expediting chart for high-voltage electronic tubes. Red tag, salvage tube. White tag, serviceable tube. Green tag, retest tube.

ED 4035 RESTRICTED

CHANNEL TERMINATION CHECK

Part I

Run No. ______________ Channel No. ______________

Run: Normal [ ] Incomplete [ ] a.m.

Reported: Date ______________ Time ____________ p.m.

Reported By: ____

Refining Division Operation Foreman

ELECTRICAL SERVICING GROUP

Part II

1. Check cubicle folder; if 30 or 60 day check is due, notify the Refining Dispatcher .... _____
2. Block main contactor (K-101) .... _____
3. Reset Cramer Timer in 9204-3 .... _____
4. Check grounding hooks and system ground at tank ... _____
5. Check and calibrate "H" heater recorder .... _____
6. Remove Dummy Thermohm and leave tank doors open ... _____

Part III

7. Open main disconnect .... _____
8. Clean meters, and glass inside cubicle .... _____
9. Reset PAC relay flags, inspect control rods, check contactors for sticking .... _____
10. Check cubicle grounding hooks .... _____
11. Record cubicle water flow .... _____
12. Complete 30 or 60 day check if due .... _____
13. Close main disconnect switch .... _____
14. Set heater currents upon notification ..."H" Amps . _____
"J" Amps . _____

Part IV

CHANNEL READY FOR INTERLOCK CHECK

Time: ________ a.m. p.m. Run No. ________ By: ____________________

Operating Foreman

Part V

15. Remove safety block from K-101 .... _____
16. Check safety interlocks .... _____
    a. Four cubicle doors .... _____
    b. Permissive switch .... _____
    c. Key interlock .... _____
    d. Emergency switch .... _____
    e. Shelf barrier interlock .... _____
    f. Bin door interlock .... _____
17. Close bin doors, return channel to operating condition .... _____

Part VI

Check made by ____

Approved by ____

Electrical Foreman or Group Leader

Received for operation: Date ____________ Time _______ a.m. p.m.

____

Operating Foreman

Fig. 5.29—Typical channel-termination check sheet.

ED 4014-1

CHANNEL ELECTRICAL INSPECTION AND MAINTENANCE CHECK SHEET
REFINING ELECTRIC

Channel

30 Day Check Date:						
A. H.V. Cubicle - remove dust from tubes, insulators, Lapp coils, cubicle windows,etc. Use vacuum cleaner on floor.						
B. Inspect all IAC and PAC relays. Use checker to test and set relays per ED 404-3.						
C. Set emission on 893 Regulator and 562 Limiter tubes per ED 404-3. Check all H.V. Tube filament voltages and connections.						
D. Heater Cubicle - clean tubes, panels, and transformers. Inspect contactors, wipe dust off transformers on mezzanine.						
E. Rheostats - check coarse and fine H.V. rheostats for free operation, loose knobs or shafts. Replace brushes where excessively worn.						
F. Inspect H.V. cubicle contactors and make necessary repairs.						
G. Grounding relays - check mechanical operation of K117, K129, K131, K132 (9204-1); K709, K747 (9204-2, -3, -4).						
H. Check all main 460 volt connections for tightness.						
I. Check water flow switches electrically, and for free float operation.						
J. Check fuses for looseness in clips or discoloration.						
K. Check PIG supply with dummy load.						
L. Check K connections inside of junction box.						
Foreman:						
60 Day Check Date:						
A. Inspect and oil Micromax (see ED 117) or Bailey Meter per ED 716.						
B. Calibrate Oscilloscope as per ED 403-1.						
Foreman:						
12 Mos. Check (Approx.) Coordinate with Vacuum Manifold Check Date:						
A. Lubricate blower motor in each cubicle (ED 135)						
B. Overhaul and lubricate "K" rectifier fan motor (ED 135)						
C. Lubricate induction voltage regulators (ED 135) (Check ED 135)						
D. Insulating oil sample and test (ED 116-1)						
E. Micromax motor to be checked as per L & N Instruction Book 1235 - Page 33						
Foreman:						

Fig. 5.30 — Typical channel electrical inspection and maintenance check sheet.

RESTRICTED

ED 1021
CEW-TEC

ELECTRICAL EQUIPMENT
TROUBLE REPORT

Bldg.______
Track______

Reported: Date______ Time______ A. M. / P. M. Channel No.______

Reported by: ______
(Name)

Nature of trouble______

Time servicing should be started______

OK'ed for Corrections: ______
Electrical Foreman

Servicing started by:

______ Time ______ A. M. / P. M. Date______

Actual Cause of Trouble and How Corrected: ______

Parts Replaced:

Servicing Completed By:

______ Time ______ A. M. / P. M. Date______

Total Electrical Outage ______ hrs. Code No. E-1
(From Process Records) ______ hrs. Code No.______

Equipment Received: Approved by:

______ Production Division Foreman

______ Electrical Foreman

RESTRICTED

Fig. 5.31 — Typical trouble-report sheet.

Chapter 6

HIGH-VOLTAGE-RECTIFIER STUDIES

In this chapter some of the experimental and theoretical studies that were made by CEW-TEC on the high-voltage-rectifier equipment used for plant operation will be discussed. It should be borne in mind that because this was primarily a production plant such experimental studies were held at a minimum and were made only when necessary owing to changing operating conditions, failure of some portion of the equipment, or a change in the equipment or control circuit. Lack of time and personnel held such experimental work strictly to a minimum.

1. RECTIFIER-REGULATION CURVES

Two typical regulation curves for the accell rectifier of the Alpha I process are shown in Fig. 6.1. The first curve represents a rectifier no-load voltage of 25 kv, and the second curve shows a rectifier no-load voltage of 10 kv. It should be remembered that the accell rectifier in normal operation was operated with the filaments of the rectifier tubes below the rated value in order that these tubes could operate emission-limited as a protection for the operating equipment. The two curves shown in Fig. 6.1 are representative of such an emission-limited accell rectifier as used in the Alpha I plant.

Curve A of Fig. 6.2 is a representative regulation curve for an Alpha I decell rectifier operating with a no-load voltage of 51 kv. The decell rectifiers in the Alpha I equipment were operated with their tubes at rated filament voltage and with the maximum amount of current delivered to the load being limited by the limiter tube. Curve B of Fig. 6.2 is representative of the maximum amount of current delivered to the load by a normally operated rectifier since this curve includes the regulator- and limiter-tube losses.

The relation of the limiter and regulator tubes to the high-voltage rectifier for the three types of high-voltage supply was shown in the

high-voltage block diagrams included in Chap. 1, Figs. 1.1 to 1.3. It was pointed out in the description of these block diagrams that the decell rectifiers in all cases were equipped with a limiter and a losser regulator. Although the detailed operation of this limiter and regulator have not yet been described, the regulation curves shown in this section include the over-all regulation when these tubes are in the circuit. This is done in order that these regulation curves will be representative of the over-all high-voltage system and will show the voltage and current relation existing at the mass-spectrograph load. A detailed description of the limiter and electronic regulator is given in Chap. 7.

In an attempt to minimize the number of rectifier-tube failures due to arc-backs in the Alpha I decell rectifier and at the same time to minimize the number of filter-capacitor failures, a study was made to find the minimum filtering that would give satisfactory operation with this rectifier. Tests were made using filter-capacitor values of 0.75, 0.50, and 0.25 μf. Rectifier-regulation curves for these three values of filter capacitors used in the Alpha I decell rectifier are shown in Fig. 6.3. The change in the output ripple voltage from this rectifier as a function of the value of the filter capacitor used is shown by the bottom set of curves in Fig. 6.3. This second set of curves indicates the value of the ripple voltage that had to be eliminated by the degenerative action of the electronic regulator for satisfactory operation. It was found from this test that with a filter capacitor of only 0.25 μf the electronic regulator reduced the 625-volt ripple existing at the output of the filtered rectifier to a value of less than 4 volts at the output of the regulated supply. With a filter capacitor having a value of 0.50 to 0.75 μf the resultant ripple voltage at the output of the regulated supply was approximately 2.1 volts. Since the specified maximum ripple for operation of the mass spectrograph was 14 volts, it is obvious that a filter capacitor of only 0.25 μf in conjunction with the electronic regulator would have been ample to reduce the output ripple voltage of the rectifier to a satisfactory value. It was also found during this test that a filter on the output of the rectifier was absolutely necessary because, when the output was not filtered, arcing would occur between the high-voltage lines and ground in the cubicle, making it almost impossible to energize the rectifier.

Curve A of Fig. 6.4 is the regulation curve of an Alpha II decell rectifier with the primary voltage to the rectifier transformer held constant. Curve B, Fig. 6.4, shows the over-all regulation of the high-voltage power supply since it includes the effect of the regulator tube and the regulation of the supply line to the rectifier.

The effect of changing filament voltage of the rectifier tubes in the Alpha II decell rectifier is shown by the three curves given in Fig. 6.5. Since an increase in rectifier-tube life usually accompanied a decrease in filament voltage, curves of this type were plotted to determine accurately the minimum allowable filament voltage in order that these rectifier tubes would not at any time be emission-limited. In Fig. 6.5 curve A shows the correct value of filament voltage when no limiting occurred, and curve B indicates a small degree of emission-limiting, approximately 2.8 amp. Curve C of this figure indicates that emission-limiting had started at a current of the order of 2.4 amp.

Tests were made using a Beta high-voltage cubicle to determine the optimum operating conditions for obtaining the maximum output voltage from the decell-rectifier supply of this type of cubicle. Figure 6.6 compares the regulation of the decell rectifier when the General Electric KC-4 rectifier tube is used with the regulation of the decell rectifier when the Machlett ML-100 rectifier tube is used. Curves are shown in this figure both for the regulation of the rectifier unit and for the regulation of the rectifier plus the electronic regulator. In both cases the solid curve indicates the characteristics obtained when General Electric KC-4 rectifier tubes are used and the dashed curve indicates the improvement that was obtained when Machlett ML-100 rectifier tubes were substituted in this rectifier.

At the same time the above tests were made, tests were also made to determine the optimum value for the emission-limit setting of the regulator tube in the Beta decell supply. At that time, owing to plant operation, it was desired to operate the mass spectrograph at approximately 39 kv with a maximum load current of 1.0 amp. Because such equipment should be operated with the regulator tube set for the minimum permissible value of emission-limiting in order to limit the short-circuit current from the decell supply, it became necessary to determine this minimum value. In order to do this, regulation curves for the decell supply were plotted (Fig. 6.7). One curve is for an emission-limit value of 1.4 amp, and the other is for an emission-limit value of 1.2 amp. In both these tests the grid of the regulator tube was connected to its cathode, thus presenting zero grid bias and the minimum regulator-tube drop. From the curves in Fig. 6.7 it can readily be seen that in order to operate the Beta decell supply at a current of 1.0 amp and an output voltage of 39 kv, it is necessary to emission-limit the regulator tube to 1.3 amp. The theory of emission-limiting will be more fully discussed in Chap. 7.

2. DIAMETRICAL 6-PHASE CONNECTION OF ALPHA I DECELL RECTIFIER

Many experiments were made in an attempt to remedy in the Alpha I decell rectifier such defects as flashovers between high-voltage bushings and between high-voltage bushings and ground and the high failure rate of rectifier tubes due to inverse voltage. It was known that when subjected to frequent high-voltage surge conditions these rectifiers were unstable and that the interphase transformers contributed to the instability. Tests conducted by the General Electric Company confirmed the existence of voltages of the order of 150 kv between the end points of the interphase transformer and between the high-voltage bushings.

In an attempt to prevent such high inverse voltages from being applied to the tubes and other equipment in this rectifier, an experiment was made in which the interphase transformer was removed from the circuit and the rectifier was operated with a 6-phase diametrical connection. Two such installations were made in Alpha I cubicles. This 6-phase diametrical connection gave an increase in the rectifier output voltage. The same output current subjected the rectifier tubes and transformer windings to a higher peak current than in the previous case in which the double 3-phase with interphase transformer connection was used. In order to carry out this test it was necessary to replace the KC-4 tubes in the rectifier with ML-100 tubes since the peak emission of the KC-4 rectifier tube was not equal to the required load current. The regulation curve for an Alpha I decell rectifier connected 6-phase star and using ML-100 rectifier tubes is shown in Fig. 6.8.

Two rectifiers using the modification described above were in operation in the Alpha I plant for a period of approximately two months, operating at a load current of 1.0 amp and a load voltage of 37.0 kv. During this period of operation neither transformer failed or indicated a temperature rise above the name-plate rating, even though this type of connection resulted in a smaller transformer copper-utilization factor. This type of rectifier connection definitely reduced the number of bushing-to-bushing and bushing-to-ground flashovers but did not completely eliminate them.

During a two-month test of these two rectifiers only one rectifier tube failed. During the same period it was found that for the double Y with interphase connection the average number of tube failures per cubicle per rectifier was seven. This test was still in progress at the time Alpha I plant operation was discontinued, and serious con-

sideration was being given at that time to expanding the test to include 48 Alpha I decell rectifiers.

3. OPERATION OF ALPHA I AND BETA DECELL RECTIFIERS AT 170 PER CENT RATED CURRENT

In experiments made to increase plant production in both Alpha I and Beta, changes were made in the tank equipment which required the decell rectifiers in each of these two processes to deliver load current of the order of 1.5 amp. A preliminary survey indicated that if this could be done the increase in production would justify a considerable decrease in equipment life. Preliminary work that had been done on the operation of Alpha I rectifier at higher peak current (Sec. 2) seemed to indicate that, in all probability, this rectifier could supply currents of the order of 1.5 amp without causing failure of any of the equipment. It was therefore decided to proceed with such a test on a limited number of rectifiers.

In the Alpha I equipment it was necessary to make the following changes in order that the high voltage supplied could be operated with a load current of 1.5 amp.

1. The 200-ohm 200-watt filter-capacitor charge and discharge resistors were replaced with 100-ohm 400-watt resistors.
2. The existing rectifier tubes were replaced with Machlett ML-100 tubes, which operated with 20.0 volts on their filaments.
3. The decell-rectifier ammeter was replaced with a meter having a range of 0 to 3 amp.
4. The overload relays and emission-limit settings of the limiter tubes were reset for the higher operating-current value.

With these modifications Alpha I decell rectifiers were operated for a period of over 1½ months with an actual load voltage of 37 kv and a load current of 1.7 amp. The emission limit of the current-limiting tubes was set for 2.2 amp. Under sparking conditions the rectifiers were required to deliver this load current of 2.2 amp for a period of 2 sec.

While operating under these conditions none of the rectifier transformers failed or showed a temperature rise above their nameplate ratings. The ML-100 rectifier tubes had a failure rate comparable to the failure rate of the tubes used in the normally operated rectifiers. Because the filter charge and discharge resistors were of adequate rating, no failures were experienced, and the supply induction voltage regulators for the rectifiers did not fail or indicate excessive temperature rises.

In the Beta rectifier equipment the following changes were necessary in order to operate the equipment at a current of 1.2 amp.

1. A current transformer with a ratio of 20 to 1 was substituted for the 10 to 1 transformer in the primary of the decell supply.
2. A current transformer with a ratio of 10 to 1 was substituted for the 3.5 to 1 transformer used in the accell supply.
3. Machlett ML-100 rectifier tubes were substituted for General Electric KC-4 tubes in the decell supply and were operated at a filament voltage of 20.0 volts.
4. An ammeter of 0 to 3 amp range was installed in place of the 0- to 1.5-amp meter in the decell supply.
5. The relay settings and emission limits of the regulator and limiter tubes were changed to meet the new conditions.

Four Beta high-voltage rectifiers were modified, as described above, and operated for a period of approximately two months. During this period of operation the decell-rectifier load current was 1.2 amp, and the load voltage was approximately 36 kv. The accell-rectifier load current never exceeded 0.3 amp at a maximum of 40 kv. During this experiment no major failures were experienced in any portion of the high-voltage equipment, and tube failures were not in excess of normal for a standard rectifier. The actual relay settings and emission limits used in this experiment are given in Table 6.1. This tabulation is also typical for the Alpha I experiment described above.

4. CONVERSION OF ALPHA I ACCELL RECTIFIER TO FULL WAVE

The Alpha I accell rectifier, as originally described, had a voltage output of only approximately 20 kv, but the accell rectifier for Alpha II and Beta had been designed for 40 kv. Because the latter units had been operated successfully at 40 kv, it was felt that an increase to 40 kv for Alpha I would materially increase production. It was therefore decided to install a 40-kv rectifier in one Alpha I cubicle in order to determine whether the theoretical increase in production could be realized in actual operation. In order to obtain a 40-kv supply the existing accell zigzag-Y rectifier was converted to a full-wave rectifier, using for the high-voltage transformer the zigzag-Y-connected transformer used in the original accell rectifier. This was an efficient means of doubling the voltage output of the rectifier with a minimum of additional equipment. The only additional apparatus required for this conversion was three rectifier tubes and one insulating filament transformer to supply the filaments of the

three additional tubes. This modification, in addition to giving double the voltage of the original rectifier, was also advantageous in that the output voltage had a lower ripple content, the rectifier was damped on transients, and full utilization of the secondary copper was realized.

In order to test this rectifier in the shortest possible time, the initial test was made in an enclosed cage installed outside the high-voltage cubicle. In this installation two accell rectifier transformers were used. One transformer was the high-voltage supply and filament supply for three of the rectifier tubes. The other transformer was used only as an insulating transformer to supply the other three tube filaments. Standard rectifier tubes were used in this installation and were operated below their rated filament voltage at a value at which they tended to emission-limit on load sparks but at a value at which the plate did not overheat on such sparks.

During the test this rectifier operated continuously at 40 kv between 0.2 to 0.4 amp. Neither the transformers nor supply induction-voltage regulator indicated temperature rises above their name-plate ratings. The tube-failure rate was approximately the same as that on a normally operated accell rectifier. This test indicated that using a full-wave rectifier that utilized the existing accell rectifier transformer would be an efficient and inexpensive way of converting the high-voltage supply to deliver simultaneously 38 and 78 kv to the load. In order that all the equipment might be placed inside the high-voltage cubicle, rectifier tubes of smaller physical size for use in the full-wave rectifier were developed by Machlett laboratories. Design work on the installation of equipment using the newly designed tubes inside the high-voltage cubicle was begun. This design, however, was not completed before the Alpha I plant operation was discontinued. In fact the period of operation for the test installation described above was so short that no conclusion can be drawn as to transformer or cable life.

5. RECTIFIER-TUBE BARRIERS

Numerous arc-overs occurred between bushings on the rectifier transformer and from the bushings to the grounded enclosure of the high-voltage cubicle. Several attempts were made to prevent such arc-overs by increasing the air-gap distance both between the high-voltage bushings and between the high-voltage bushings and the cubicle wall. One such attempt to correct this arc-over trouble was made by wrapping the bare portion of the rectifier-tube base and tube socket with several layers of varnished-cambric tape. The arcs that then occurred did not puncture the tape but occurred through the

air passing under the tape. Although this procedure decreased the frequency with which arc-overs occurred, it was not satisfactory for plant operation since it materially increased the time required for changing rectifier tubes because the tube sockets required unwrapping and rewrapping at the time of tube replacement. A second attempt was made to increase the air gap between the high-voltage bushing and between the bushings and cubicle wall by using insulating barriers in the form of cylinders around each of the bushings. These barriers increased the air gap between bushings and between bushings and the cubicle wall to a sufficient distance to prevent arc-overs. These tests were conducted in the Alpha I plant near the end of plant operation and, although no transformer failure occurred, the length of the test was too short to give conclusive results. One opinion, however, held that the bushings acted as protective gaps and that arc-overs served as protection for the transformers.

6. RECTIFIER-TUBE ANODE RESISTORS

The General Electric Company recommended that 50-ohm resistors be placed in the anode circuit of each of the rectifier tubes in the decell rectifiers. This recommendation was made for the reason that in the rectifier of a water-cooled-tube tester used at the factory of the General Electric Company a tube-failure rate of one tube per day had been experienced, but after resistors had been placed in the anode circuit of the rectifier tubes, this rate of failure decreased to one tube every ten days. No theoretical explanation was ever given.

At the request of General Electric several installations of these resistors were made in plant rectifiers, and records covering a considerable period of time were kept of tube failures for these rectifiers. These records indicated that the failure rate of the tubes in the rectifiers equipped with the anode resistors was comparable with failure rate of the tubes in a normal rectifier.

7. ARC-BACK INDICATORS

As has previously been discussed (Chap. 5, Sec. 2), a great many tube failures occurred because the rectifier tubes would not withstand the rectifier inverse voltage. When such a failure occurred, it was extremely difficult to determine which of the six tubes in the decell rectifier had failed. As a result various schemes were discussed, and one arrangement in which an overcurrent flag relay was placed in the anode circuit of each of the rectifier tubes was tested.

The theory of this relay was that on gas kicks the tube that had kicked would receive the output current of the remainder of the rec-

tifier tubes that were conducting at the time of the gas kick. Thus the gassy tube could be detected by setting the relay to a current value such that it would not indicate on normal operating current but would indicate on abnormal anode current.

An experimental model was constructed using six flag relays provided with suitable shunts mounted in a common enclosure, which in turn was mounted near the anodes of the decell rectifier tube in an Alpha I cubicle so that operation of the relay flags could be checked through the rear windows of the cubicle. The initial tests were started with the relays set to trip at 2.2 amp direct current. This value of current was insufficient to detect the gassy tube since in most cases on a gas kick two or more relay flags would indicate operation. The value of the relay-trip current was then increased to 3.0 amp and later to 4.0 amp. For both these current settings, when a known gassy tube was placed in one position in the rectifier circuit, this tube was indicated by arc-back-indicator operation for all tests that were made. Tests were also made with this arc-back indicator in a normal production cubicle in the hope that the indicator would be used on a plant-wide basis to detect gassy tubes. Use of this indicator would decrease the number of rectifier flashovers that necessarily caused production outage. At the time of writing, however, such arc-back indicators had not been adopted for plant operation.

8. MERCURY-VAPOR RECTIFIER TUBES

Mercury-vapor rectifier tubes were designed by General Electric as a replacement for the KC-4 used in the high-voltage cubicles. This tube, known as the "ZP-648," a mercury-vapor tube containing 15 special screens, was used as a capacity divider to obtain the necessary high peak inverse voltage rating. The tube had a 5-volt 10-amp filament and an arc drop of 25 to 30 volts. The tube was rated at 2.5 amp average plate current with a peak inverse voltage rating of 150 kv.

The problems occurring with the installation of the General Electric type ZP-648 mercury-vapor tubes included a change of filament transformer, installation of thermostatically controlled heaters and air-velocity interlocks in the air ducts, and installation of line reactors in the primary circuit of the decell transformer. The reactors were necessary owing to the low tube drop and because the mercury-vapor tubes would not emission-limit during the periodic short-circuit conditions imposed on the decell rectifiers. It was felt that the transformer windings would soon be torn to shreds under these short-circuit conditions if the reactors were not put into the supply lines.

Replacement of existing rectifier tubes with ZP-648 tubes was not justified. The following factors entered into the decision:

1. The number of changes involved in making a plant-wide change would have resulted in considerable lost production time.

2. The line reactor required in the primary circuit of the rectifier would have resulted in lower output voltage than was then required for plant operation.

3. The ratings of the tube were not within the normal design ranges for mercury-vapor tubes.

4. Satisfactory high-vacuum rectifiers were being supplied by other manufacturers.

However, it was agreed to test a group of ZP-648 tubes in the decell rectifiers of an Alpha I cubicle to secure information for the General Electric Company. Before the necessary equipment was received for a test of the ZP-648, the Alpha I plant was shut down, and it became necessary to change the location of this test. Arrangements were then made to test the tubes in an experimental cubicle. The cubicle in which these tubes were tested was made inoperative at the end of 5,686 filament hours by continuous arc-back in the tubes. Replacing one of the tubes remedied this difficulty temporarily.

The next day the same failure recurred. An examination showed that the temperature of the tubes was above normal and that a large portion of the cooling air was being diverted for other uses. Elimination of this diversion of the cooling air returned operation to normal.

It is to be pointed out that, at the time of this writing, even though the filament hours totaled 5,686, the number of anode hours was only 1,708. However, in those 1,708 hr the tubes had been energized and deenergized a total of 33,672 times, or almost 20 times for every hour of actual rectifying service.

The ZP-648 is included in the group photograph, Fig. 6.9.

9. ELECTRONIC SWITCHING

Owing to the heavy-duty cycle imposed by tank overloads and recycling on the rectifier step-start contactors and the main-supply contactors, several schemes for other switching circuits were suggested for use with the high-voltage rectifiers. One scheme that was tried in Alpha I was to use the diode limiter tube as an electronic disconnector by turning off its filament during periods of overload.

A test was conducted in which the IAC overload relays turned the limiter-tube filament off and on instead of operating the step-start contactor. It was observed that under conditions of extreme limiting using this process the accell-rectifier load current would become

excessive. This condition in turn brought about an operation of the accell-rectifier IAC relay, which initiated a series of such cycles. In order to eliminate this undesirable condition a refinement of the original scheme was next tried. This modification was made by adding a resistor in series with the primary leads of the accell induction regulator and a contactor for shorting these resistors during normal operation. Thus the resistors in the primary of the accell rectifier were in the circuit only during the time when the limiter-tube filament was deenergized by a decell-rectifier overload.

Unfortunately few process operators made use of this device because a switch was provided to make it inoperative during abnormal tank conditions and during the start-up period. Consequently little information was obtained even though the system was still installed at the time of the Alpha I plant shutdown. From the small amount of available information it appeared that this scheme was feasible. It should be pointed out that the time required for the filament of the limiter tube to reach operating temperature after the filament circuit had been energized was an important consideration in the design of the system since during the time required for the filament to reach operating temperature the decell voltage was below normal and swept the ion beam across the U 235 receiver electrode. This gave contamination inversely proportional to the velocity of the beam at the point where it crossed electrodes. However, it was found that the heating time of a GL-562 tube used in the limiter position was short enough to minimize such contamination.

10. UNDERVOLTAGE PROTECTIVE CIRCUIT

Under certain conditions of cubicle operation when emission limiting was employed (discussed in Chap. 7) it was possible that the emission-limiting value might fall below the tripping value of the IAC overload relays. Under this condition the load current due to an arc occurring in the tank would not cause the relays to trip but could cause severe damage to the tank equipment. When such an arc occurred, however, the decell voltage would be reduced considerably below 35 kv. Under these conditions it was necessary for the cubicle operator to deenergize the high-voltage supply in order to extinguish the arc. As a result it was felt that it might be more advantageous to use an undervoltage protective device than to use overcurrent protective relays such as had been provided in the initial equipment.

Such an undervoltage protective relay was developed and tested. A schematic diagram of this device is given in Fig. 6.10. The operation of this undervoltage device as installed in an Alpha II cubicle will now be explained.

If it is assumed that the decell voltage was 40 kv, approximately 40 volts existed across resistor R_7. The positive side of this resistor was connected through the contact (normally closed) of relay K1B to condenser C_2. This condenser in turn was charged to approximately 40 volts through the diode section of the 6SQ7 tube. Under these conditions the grid voltage of the 6SQ7 was essentially zero, thus allowing plate current to flow and charge the condenser C_3 to approximately 60 volts. The voltage across the condenser C_3, being the grid voltage of the 2051 tube and being negative with respect to its cathode, prevented this tube from firing, thereby keeping relay K1 deenergized as long as such voltage existed.

If, owing to sparking in the tank, the decell voltage dropped to 35 kv, for example, the voltage existing across R_7 in turn decreased to 35 volts. Although this condition existed, C_2 discharged through the 20-megohm resistor R_3, causing the grid of the 6SQ7 to be driven to a negative potential of approximately 5 volts. This in turn caused cutoff in the anode circuit of the 6SQ7. This condition was maintained for several seconds owing to the time constant of C_2 and R_3. When the plate current of the 6SQ7 had been cut off, C_3 discharged through resistor R_4, the time constant of this circuit being such that C_3 discharged to approximately 20 volts in 1 sec. At this voltage the 2051 tube was caused to fire, owing to the opposing a-c voltage of approximately 18 volts peak which existed across resistor R_5. The opposing voltage was taken from the voltage-divider circuit C_4-R_5. When the 2051 tube fired, it energized relay coil K1A, closing contacts K1D connected in parallel with the IAC overload-relay contacts, thus initiating a normal recycler operation. At the same time contact K1B opened and contact K1C closed, discharging condenser C_2 through resistor R_1 with the time constant of the circuit being such that this condenser discharged to less than 1 volt in approximately 0.5 sec. When the grid voltage of the 6SQ7 had been reduced to less than 1 volt, plate current flowed, charging condenser C_3. This caused the 2051 tube to cease conducting, thus deenergizing relay coil K1A. The circuit was then in condition to operate on the next recurring undervoltage condition.

Tests were made in units of this description in Alpha II high-voltage cubicles, but such a system was never adopted for plant-wide operation.

11. OUTAGE DUE TO LOCKOUTS IN RECYCLER

In the description of the recycler circuit used in the Alpha II and Beta equipment it was pointed out that, if a second overload occurred within a specified period of time after the first overload had taken

place, the recycler would automatically lock out the high-voltage circuit and return it to manual control. In the Alpha II plant it was felt that the number of such lockouts was too great, causing excessive loss of production time. Routine checks were made by the process operators, and it was determined from these checks that a more thorough investigation should be made to determine the exact cause of the trouble. In order to carry out such an investigation a special circuit was designed to count the number of lockouts caused by failure of the recycler equipment and the number of lockouts caused by poor setting of the emission limit and relays.

These counters were installed in four cubicles, which were believed to be those on which lockouts most frequently occurred. It was found from this test that several factors affected the number of lockouts, namely, (1) time adjustment on the recycler timer, (2) instantaneous setting of the IAC relay, (3) emission limit of the 893 regulator tube, and (4) bad contacts in the control circuit of the recycler.

The results of tests conducted on these four cubicles have been tabulated in Table 6.2.

From these data it was concluded that lockouts due to recycler-equipment failure could be eliminated by replacing the control contacts that were becoming burned in operation with heavier contacts and a stronger spring. It was also felt that a more accurate means of adjusting the time delay of the recycler timer would be required. As a result new contacts and springs were installed on all the Alpha II cubicles, and 48 of these cubicles were equipped, on an experimental basis, with an added resistor in each of the electronic timers. This resistor allowed the timer adjustment to be set at maximum for the desired time.

The lockouts due to the timer circuit and bad contacts in the control circuit were eliminated by the changes described above. The number of lockouts caused by poor setting of emission limit and relays was greatly reduced when these values were adjusted according to standard procedure sheets.

A study was made of the number of lockouts occurring in the Beta equipment to determine whether such lockouts occurred with sufficient frequency to justify the addition of a warning light to the cubicle to indicate when a lockout had occurred. A series of tests was conducted over an extended period of time on certain Beta cubicles. The results of these tests indicated that the cost of the additional equipment required for a warning signal could not be justified on the basis of lost production time.

12. RELAY-COORDINATION STUDY

The high-voltage rectifiers and their supply circuits were equipped for overloads and short-circuit protection with air circuit breakers and contactors. The air circuit breakers were tripped by relays that tripped the latch mechanism holding the breaker closed, and the contactors were tripped by relays that deenergized their holding-coil circuit. The sequence of the circuit breakers, contactors, and their respective relays may be seen in Figs. 6.11 to 6.13. Since the problems were essentially the same for the Alpha I, Alpha II, and Beta equipment, the discussion will consider in detail only the problem of relay coordination in the Alpha I plant. A brief review of the essential protective equipment ratings for Alpha I is as follows:

1. Unit-substation transformer: 3-phase 60-cycle 1,000-kva 13,800/460-volt rating, 5.5 per cent impedance.
2. Unit-substation air circuit breaker: General Electric type AL-2, 3-phase 600-volt 1,600-amp 8-hr rating (5,000-amp interrupting rating), protective tripping device, dual magnetic.
3. Unit-substation cubicle-supply air circuit breaker: General Electric type AE1B, 3-phase 600-volt 450-amp 8-hr rating (2,500-amp interrupting rating), protective tripping device, dual magnetic.
4. High-voltage cubicle main power contactor: General Electric type CR2811C5AQ, 3-phase 600-volt 150-amp 8-hr rating (1,500-amp interrupting rating), protective tripping device, General Electric PAC definite time-delay relay, 5- to 15-amp current transformer, ratio 30 to 1.
5. Accell- and decell-rectifier main contactor: General Electric type CR2811CC248A, 3-phase 600-volt 150-amp 8-hr rating (1,500-amp interrupting rating).
6. Accell- and decell-rectifier auxiliary contactor: General Electric type CR2811C4AS, 3-phase 600-volt 75-amp 8-hr rating (750-amp interrupting rating).
7. Accell-rectifier protective tripping: General Electric IAC relay with 1.5- to 6-amp induction time element and 3- to 12-amp instantaneous-attachment current transformer, ratio 2 to 1.
8. Decell-rectifier protective tripping: General Electric IAC relay with 1.5- to 6-amp induction time element and 3- to 12-amp instantaneous-attachment current transformer, ratio 20 to 1.

The air circuit breakers were protected by time-delay tripping for overload and by instantaneous tripping for short circuits. The tripping device was dual magnetic, having an oil-film time delay. This time delay was actuated by the force of an electromagnet to give

time-delay tripping on currents less than approximately ten times the breaker rating and instantaneous tripping independent of the time-delay mechanism on currents in excess of approximately ten times the breaker rating. The calibration range of the time-delayed tripping was from 100 to 200 per cent of the breaker-current rating. The instantaneous tripping was not adjustable but did change slightly for different calibration settings of the time-delay mechanism. The approximate time-current characteristics for this type of device are shown in Fig. 6.14. This device, being direct acting, was mechanically connected to the overload armature, and during the period the breaker was carrying load the armature and connecting linkage between parts was subjected to vibration. Such vibration tended to wear the mechanical linkage as well as the timing disk, which depended on an oil film to give the time delay for the relay to operate. Such wear, as well as dirty oil and changes in ambient temperatures, tended to change the relay-time calibration. For these reasons accurate timing for close relay coordination was practically an impossibility.

The PAC relays used in conjunction with the cubicle main power contactor were of the plunger type, utilizing a bellows to obtain time-delay operation. The amount of time delay was obtained by adjusting the size of the opening through which the bellows exhausted air during the period of relay-plunger travel. Time-current characteristic curves for this type of relay are shown in Fig. 6.15.

The IAC relay used in connection with the main and step-start contactors were the induction disk type for time-delay operation with a plunger attachment for instantaneous operation. Characteristic curves for this type of relay are shown in Figs. 6.16 and 6.17.

The 1,000-kva unit substation had, if the 13.8-kv primary was considered an infinite bus, a short-circuit current of 22,800 amp on the station bus. This, however, was not quite the case since the transformer was supplied from a 40,000-kva 154/13.8-kv transformer that can be considered as a supply bus having 0.53 per cent impedance on a 1,000-kva basis. Thus the maximum short-circuit current at the unit substation 460-volt bus was 20,800 amp.

The supply line from the unit-substation supply breaker to the high-voltage cubicle on a 1,000-kva basis had 0.94 per cent impedance. This gave a short-circuit current of 18,000 amp on the high-voltage-cubicle main 460-volt bus.

Assuming a 1 per cent impedance on a 1,000-kva basis for the supply line to the decell rectifier and assuming the decell rectifier rated 51.5 kva with 3.6 per cent impedance, the short-circuit current of the rectifier-transformer high-voltage output when reduced to a 460-volt basis was 1,610 amp. Assuming a 2 per cent impedance on

a 1,000-kva basis for the supply line to the accell rectifier and assuming the accell rectifier rated 10 kva with 4.33 per cent impedance, the short-circuit current of the rectifier-transformer high-voltage output, when reduced to a 460-volt basis, was 284 amp. Thus from the above data it is readily seen that the fault currents available were greatly in excess of fault currents usually found in most plant installations and thus magnified the problem of protecting the equipment, both from overload and short circuit.

Both the cubicle 150-amp contactors had an interrupting rating of 1,500 amp but were called on to interrupt current of much greater magnitude than their rating. These contactors, however, for infrequent occurrence, had a maximum interrupting ability much greater than their rating. The holding-coil circuit of these contactors was supplied through a step-down transformer from the same 460-volt cubicle bus that supplied the rectifier equipment. This was not a desirable feature since on a short-circuit fault the voltage of this bus would collapse at the time of the fault, and therefore the holding coil, even though it was not deenergized by its time-delay relay, would lose its holding ability and release the contact pressure. It was found that these contactors would blow open on current in excess of 8,000 amp. Since they were subject to fault currents greatly in excess of this value, they would blow open on such faults because the air circuit breakers were not fast enough to clear these faults first. Thus the breakers tended only to limit the amount of damage done when such faults occurred.

The protective relays used in connection with the rectifier contactor to protect the rectifier equipment were utilized to give maximum protection to both the rectifier equipment and to the load served. The final relay settings in Alpha I used prior to the discontinuance of plant operation were as follows:

1. Decell-rectifier IAC relay
   a. Induction-time element: hold 1.0 amp direct current at 38 kv and trip in 1.4 sec at 1.5 amp direct current (emission-limit setting of current-limiter tube, 1.5 amp).
   b. Instantaneous element: trip on current in excess of 2.4 amp direct current.
2. Accell-rectifier IAC relay
   a. Induction-time element: hold 4.0 amp direct current at 15 kv and trip in 2 sec at 0.55 amp direct current.
   b. Instantaneous element: trip on current in excess of 0.78 amp direct current.
3. High-voltage-cubicle 460-volt-bus PAC relay: hold 150 amp alternating current and trip at 300 amp alternating current in 0.5 sec.

4. Unit-substation cubicle-supply breaker:
   a. Hold 900 amp alternating current with time delay set for half time.
   b. Instantaneous trip set for approximately 4,500 amp alternating current.
5. Unit-substation breaker:
   a. Hold 1,600 amp alternating current with time delay set for minimum time.
   b. Instantaneous trip for approximately 16,000 amp alternating current.

It should be remembered when referring to the above relay settings that each unit-substation breaker had to carry the load of three cubicle-supply breakers and that each of these cubicle-supply breakers carried the load of four high-voltage cubicles. No mention has been made of the 13.8-kv breakers, but, of course, the 460-volt breaker was coordinated with them. An approximate relay-coordination curve for the cubicle supply and equipment on a 460-volt basis is shown in Fig. 6.11.

13. REMOVAL OF STEP-START RESISTORS

During one period of operation the rate of failure of the step-start resistor became so high that it became impossible to secure sufficient resistors for replacement. It was therefore decided to remove the step-start resistors from 48 Alpha II cubicles on an experimental basis. Data were then taken of the number of trips during an 8-hr period for these cubicles as compared to the number of trips for 48 other cubicles that were equipped with step-start resistors. It was found that for the 48 cubicles in which the resistors had been removed, approximately 2,000 trips occurred in 8 hr, whereas for the cubicles having step-start resistors, only 200 trips occurred in the same period. The number of trips without step-start resistors was then decreased to about 500 by increasing the instantaneous-trip value of the overload relays. This required closer supervision by the process operators but eliminated the outage due to step-start-resistor fire. These 48 cubicles were operated for several months with the step-start resistors removed, and operation was entirely satisfactory.

14. RECTIFIER INRUSH-CURRENT STUDY

In January 1945 the effectiveness of the step-start resistors in Alpha II was studied by measuring the maximum inrush current to the accell and decell rectifiers with and without the step-start re-

sistors. This information was desired in connection with the experiment described in Sec. 13 and also because the 460-volt air circuit breakers were tripping owing to an unknown cause. The equipment used included a General Electric type PM 13 oscillograph. Current transformers were utilized to furnish the signal for the current-measuring galvanometers, and these galvanometers were shunted with suitable resistors to give the desired sensitivity. The phase voltages were measured using bleeder resistors in series with the galvanometers. These resistors were of suitable value to give the desired sensitivity.

Many oscillograms were taken, and from these representative oscillograms, which show the maximum inrush current for several conditions, have been selected and are shown in Figs. 6.18 to 6.22. These currents may be compared with the transients produced when gas kicks (arc backs) occur in a rectifier tube, Fig. 6.23. Data pertaining to each of these figures are presented in Table 6.3. It was readily apparent from these figures that the maximum peak inrush current was considerably reduced when step-start resistors were utilized. This condition has been substantiated in a previous discussion (Sec. 13). The oscillograms also indicated that the inrush current was not of sufficient magnitude to trip the 460-volt air circuit breaker when it was set up at the proper value, as indicated by the relay-coordination curve (Fig. 6.12).

Table 6.1 — Beta Relay and Emission Settings for Decell-rectifier Operation of 1.2 amp Direct Current

Main-cubicle overload relays:	
Current-transformer ratio	30 to 1
Relay coil pickup current,[a] a-c amp	7
Time-lever setting, position No.	1
Accell-rectifier overload relays:	
Current-transformer ratio	10 to 1
Instantaneous-element pickup current,[a] a-c amp	5.15[b]
Induction time element:	
Selector-plug position, amp	2.0
Pickup current,[a] a-c amp	2.58[c]
Time-lever setting, position No.	10
Decell-rectifier overload relays:	
Current-transformer ratio	20 to 1
Run period:	
Instantaneous-element pickup current,[a] a-c amp	9.0[d]
Induction time element:	
Selector-plug position, amp	2.0
Pickup current,[a] a-c amp	3.85[e]
Time-lever setting, position No.	10
Bake-out period:	
Instantaneous-element pickup current,[a] a-c amp	6.4[f]
Induction time element:	
Selector-plug position, amp	2.0
Pickup current,[a] a-c amp	2.4[g]
Time-lever setting, position No.	10
Rectifier Tubes:	
Accell rectifier	General Electric KC-4
Decell rectifier	Machlett ML-100
Filament voltage, volts	20
Emission Limit:	
Regulator tube (run and bake-out period), d-c amp	2.25
Limiter tube (run and bake-out period), d-c amp	0.7

[a]The pickup current is the minimum current required to close the relay contacts.
[b]Direct-current equivalent is 1.0 amp.
[c]Direct-current equivalent is 0.5 amp.
[d]Direct-current equivalent is 3.5 amp.
[e]Direct-current equivalent is 1.5 amp.
[f]Direct-current equivalent is 2.7 amp.
[g]Direct-current equivalent is 0.935 amp.

Table 6.2 — Alpha II Recycler Lockouts

Condition or change made in equipment	Lockouts per hour*	Lockouts per hour†
Cubicle No. 1		
As found	10.7	3.3
Change No. 1, decell supply regulator-tube emission limit reduced from 3.5 to 3.0 amp direct current	2.5	0.1
Change No. 2, resistors installed in recycler timer to give better adjustment of time	0.1	0
Cubicle No. 2		
As found. Decell instantaneous setting at 12 amp alternating current	6.0	1.1
Change No. 1, resistors installed in recycler timer to give better adjustment of time	1.6	0.1
Change No. 2, decell instantaneous setting changed from 12 to 15 amp alternating current	1.2	0.01
Cubicle No. 3		
As found	1.8	0.8
Change No. 1, resistor installed in recycler timer to give better adjustment of time	1.4	1.0
Change No. 2, contacts replaced on contactor in recycler circuit	0.08	0
Cubicle No. 4		
As found	3.0	20.0
Change No. 1, resistors installed in recycler timer to give better adjustment of time	0.06	20.0
Change No. 2, emission reduced from 4 to 3.5 amp direct current	0.01	0.03

*Due to failure of recycler equipment.
†Due to poor settings of emission limits and relays.

Table 6.3 — Data Pertaining to Figs. 6.18 to 6.23*
(Figs. 6.18 to 6.22, inrush-current oscillograms; Fig. 6.23, gas-kick-current oscillograms)

Figure	Without step-start equipment	With step-start equipment	Conditions
6.18	Voltage, 620 volts RMS I_3, 200 amp RMS I_1, 655 amp max. peak I_2, 635 amp max. peak I_3, 1030 amp max. peak	Voltage, 620 volts RMS (run); 200 volts RMS (start) I_3, 200 amp RMS I_1, 935 amp max. peak I_2, 300 amp max. peak I_3, 1280 amp max. peak	Current measured in primary of rectifier; voltage measured at primary of rectifier; rectifier output shorted
6.19	Voltage, 620 volts RMS I_3, 160 amp RMS I_1, 375 amp max. peak I_2, 342 amp max. peak I_3, 1060 amp max. peak	Voltage, 620 volts RMS (run); 345 volts RMS (start) I_3, 180 amp RMS I_1, 437 amp max. peak I_2, 450 amp max. peak I_3, 780 amp max. peak	Current measured in primary of rectifier; voltage measured at primary of rectifier; rectifier load, 2.5 amp d-c
6.20	Voltage, 800 volts RMS I_3, 100 amp RMS I_1, 140 amp max. peak I_3, 224 amp max. peak	Voltage, 800 volts RMS (run) I_3, 100 amp RMS I_1, 121 amp max. peak I_3, 103 amp max. peak	Current measured in primary of rectifier; voltage measured at primary of rectifier; rectifier load, 1.4 amp d-c
6.21	Voltage, 460 volts RMS I_3, 175 amp RMS I_1, 630 amp max. peak I_2, 732 amp max. peak I_3, 840 amp max. peak	Voltage, 460 volts RMS (run); 360 volts RMS (start) I_3, 175 amp RMS I_1, 240 amp max. peak I_2, 300 amp max. peak I_3, 350 amp max. peak	Current measured in 460-volt supply line; current measured on load side of step-start equipment; load on decell rectifier, 1.75 amp d-c; load on accell rectifier, 0.45 amp d-c
6.22	Voltage, 460 volts RMS I_3, 200 amp RMS I_1, 560 amp max. peak I_2, 840 amp max. peak I_3, 700 amp max. peak	Voltage, 460 volts RMS (run); 350 volts RMS (start) I_3, 200 amp RMS I_1, 590 amp max. peak I_2, 590 amp max. peak I_3, 440 amp max. peak	Current measured in 460-volt supply line; voltage measured on load side of step-start equipment; load on decell rectifier, 2.50 amp d-c; load on accell rectifier, 1.40 amp d-c

Figure	Gas-kick-current oscillograms	Conditions
6.23	Voltage, 620 volts RMS I_3, 200 amp RMS I_1, 160 amp RMS; 655 amp max. peak I_2, 260 amp RMS; 1,220 amp max. peak I_3, 200 amp RMS; 470 amp max. peak	Current measured in primary of rectifier; voltage measured at primary of rectifier; rectifier output shorted

*In these figures the order of the separate wave forms is as follows, from top to bottom: I_1, I_2, I_3, and voltage.

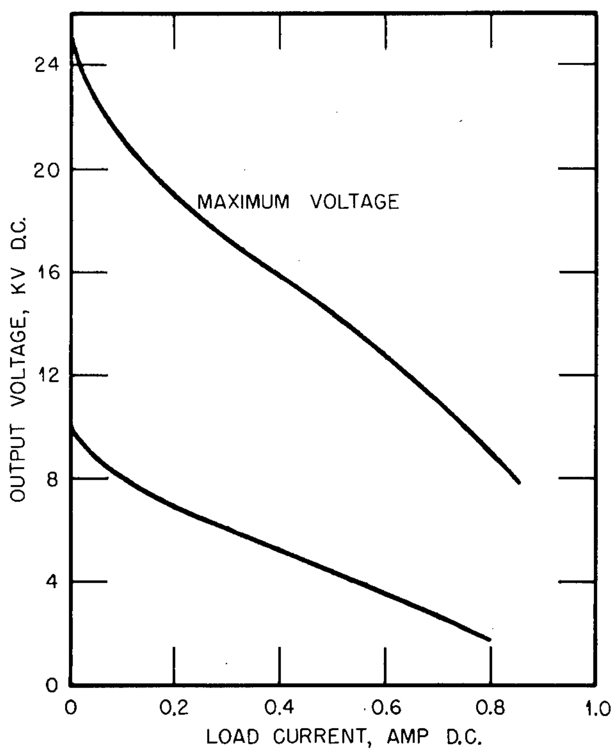


Fig. 6.1 — Typical regulation curve of the Alpha I accell rectifier. General Electric KC-4 rectifier tube used with filament voltage of 18.6 volts. Curves include regulation of rectifier-transformer-supply circuit.

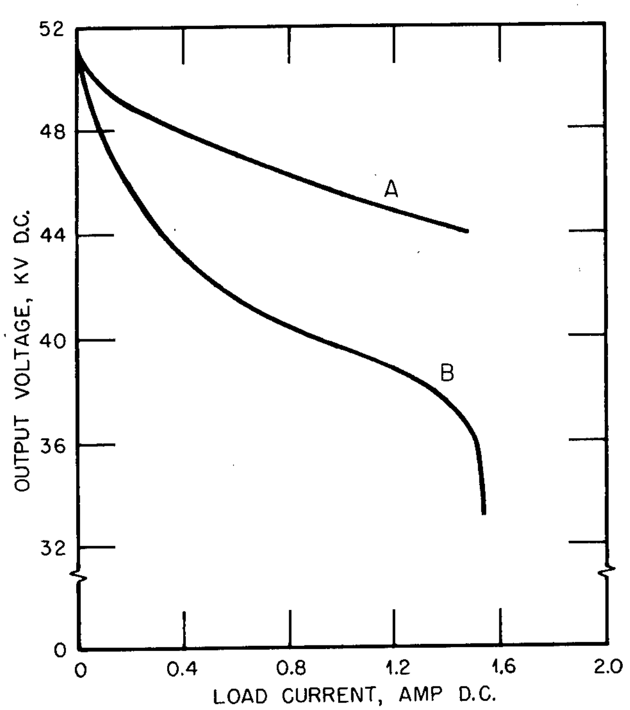


Fig. 6.2 — Typical regulation curve for Alpha I decell rectifier. Rectifier tube, General Electric KC-4; filament voltage is 20 volts. Regulator tube, General Electric GL-893, rated filament voltage. Limiter tube, General Electric GL-562; emission-limit setting is 1.5 amp. Curves include regulation of rectifier-transformer-supply circuit. Curve A, regulation at rectifier filter. Curve B, regulation including regulator and limiter tube.

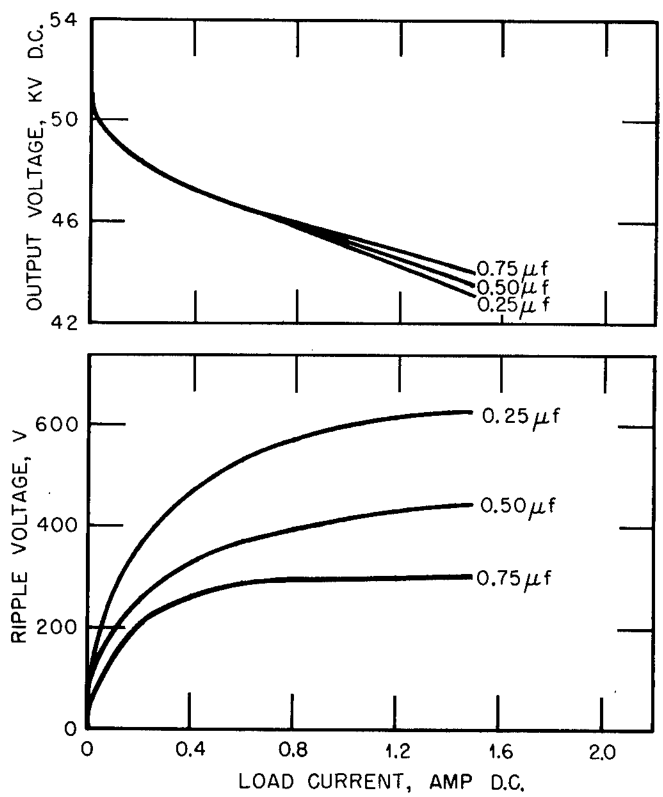


Fig. 6.3 — Typical regulation curves for different degrees of filtering in the Alpha I decell rectifier. Curves show regulation at rectifier filter and include regulation of rectifier-transformer-supply circuit.

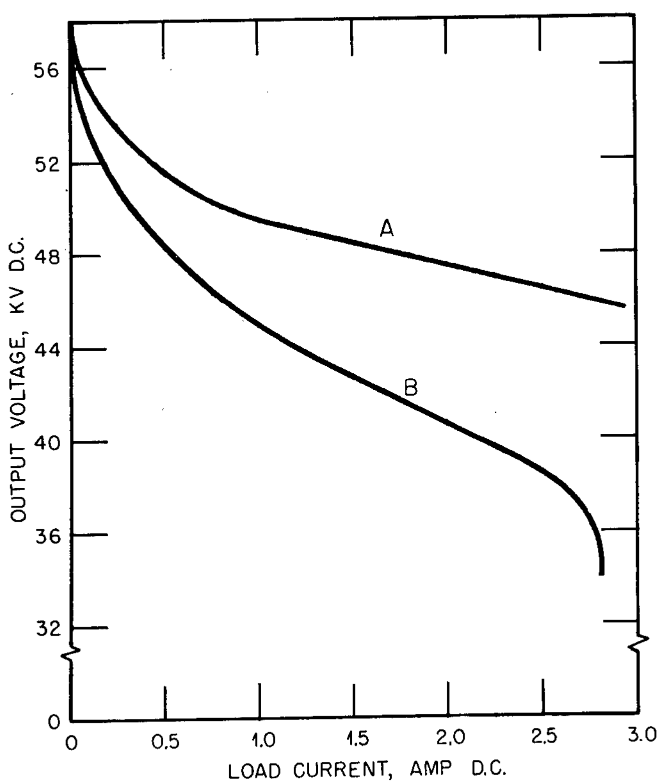


Fig. 6.4 — Typical regulation curve for Alpha II decell rectifier. Curve A, regulation at rectifier filter. Curve B, regulation including regulator tube. Curves include regulation of rectifier-transformer-supply circuit. Regulator tubes, two General Electric GL-893 tubes in parallel. Emission-limit setting is 3.0 amp.

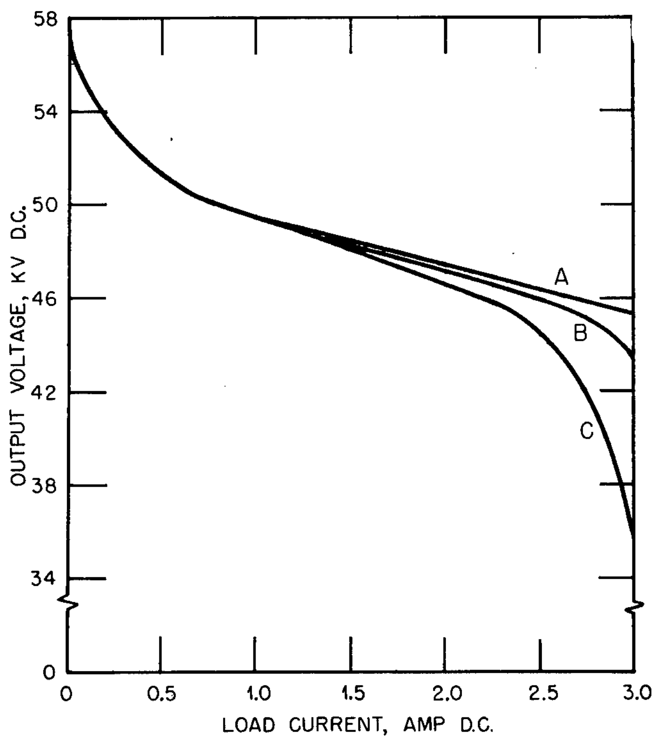


Fig. 6.5 — Typical regulation curves for different rectifier-tube filament voltage in Alpha II decell rectifier. Rectifier tube, Federal F-660. Curves show regulation at rectifier filter and include regulation of rectifier-transformer-supply circuit. Curve A, E_F is 20.3 volts. Curve B, E_F is 19.8 volts. Curve C, E_F is 19.2 volts.

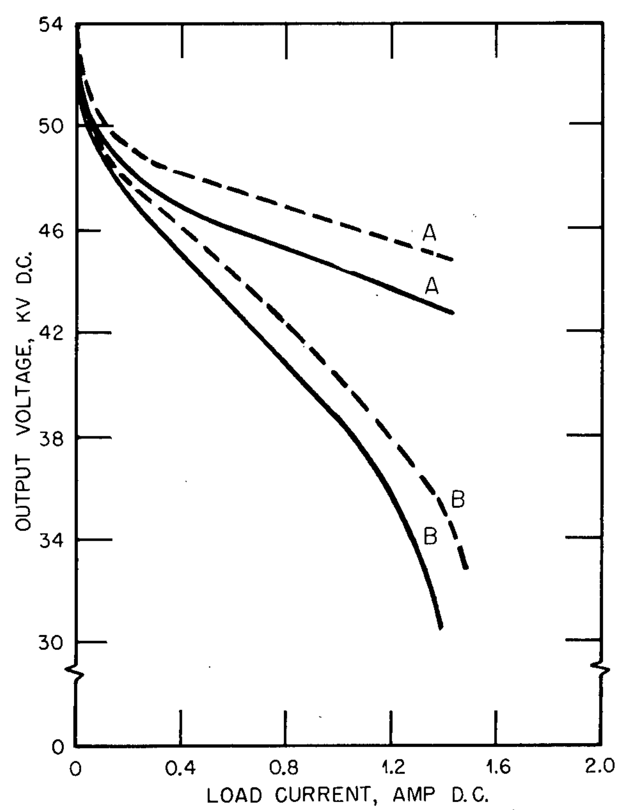


Fig. 6.6—Typical regulation curves for two types of rectifier tubes in Beta decell rectifier. Dashed curves, Machlett ML-100. Solid curves, General Electric KC-4. Curves include regulation of rectifier-transformer-supply circuit. Curves A, regulation at filter. Curves B, regulation including regulator tube.

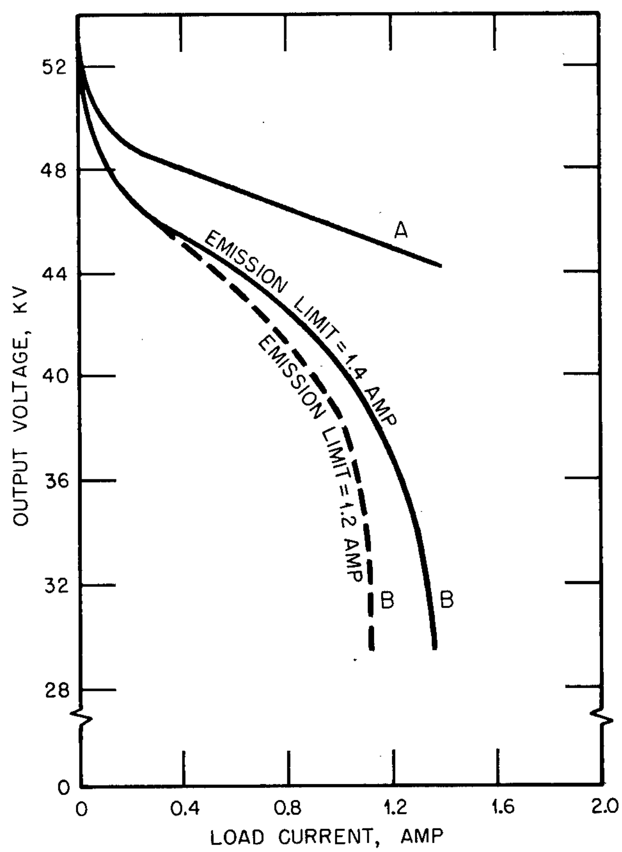


Fig. 6.7—Typical regulation curves for different regulator-tube emission-limit values in Beta decell rectifier. Rectifier tubes are Machlett ML-100; filament voltage is 20 volts. Curves include regulation of rectifier-transformer-supply circuit. Curve A, regulation at rectifier filter. Curves B, regulation including regulator tube.

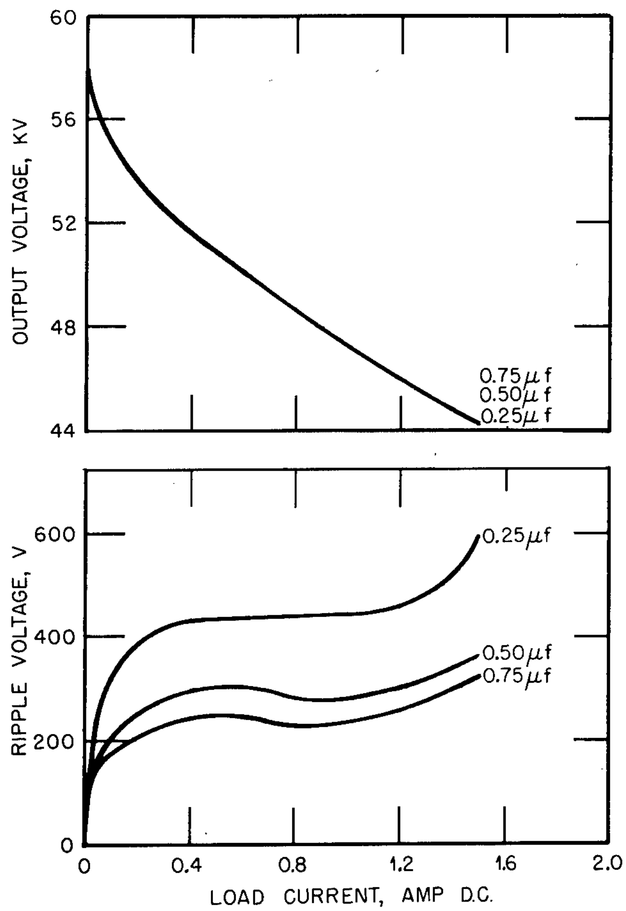


Fig. 6.8—Typical regulation curves for 6-phase diametrical connection with different degrees of filtering in Alpha I decell rectifier. Curves show regulation at rectifier filter and include regulation of rectifier-transformer-supply circuit.

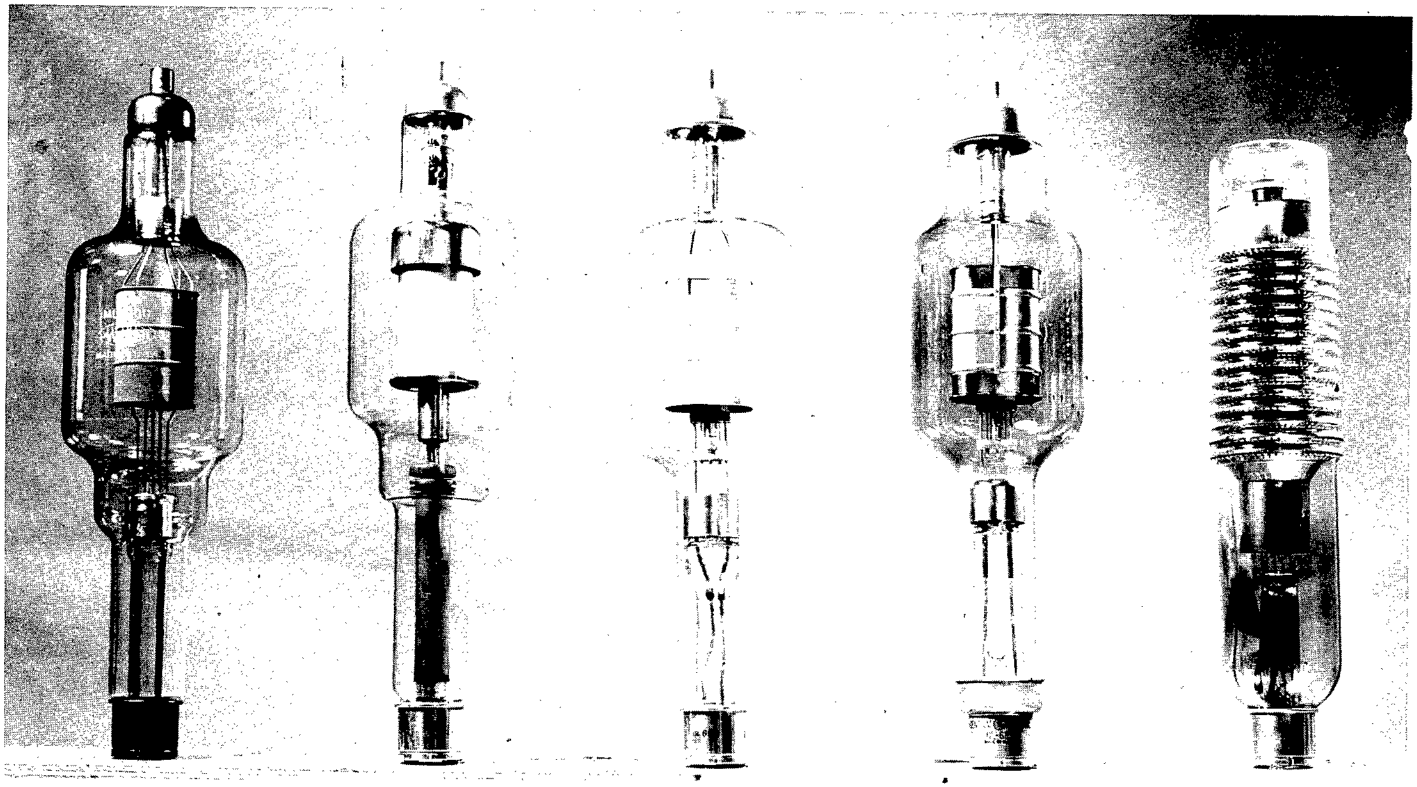


Fig. 6.9 — Experimental radiation-cooled rectifier tubes. Left to right: ML-200, WL-619, ZP-681, GL-681, and ZP-648 (mercury vapor).

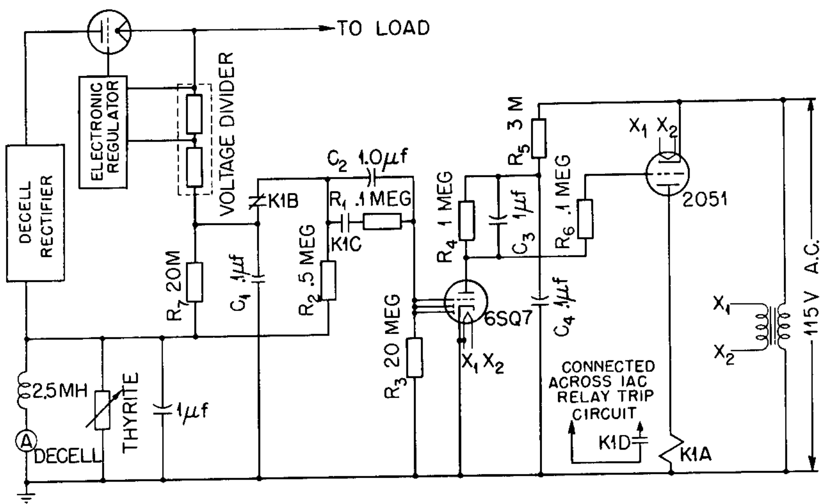


Fig. 6.10—Schematic diagram of undervoltage protective circuit.

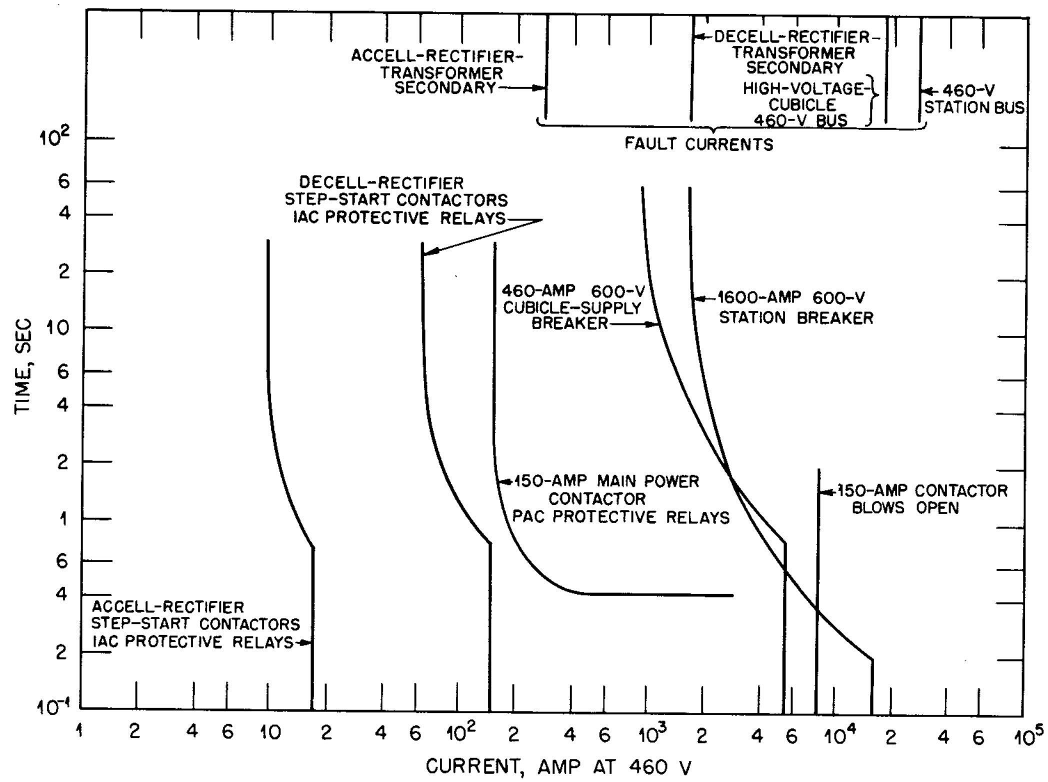


Fig. 6.11 — Typical relay coordination curve in Alpha I. Note that curves indicate the time required for the contactors and breakers to open.

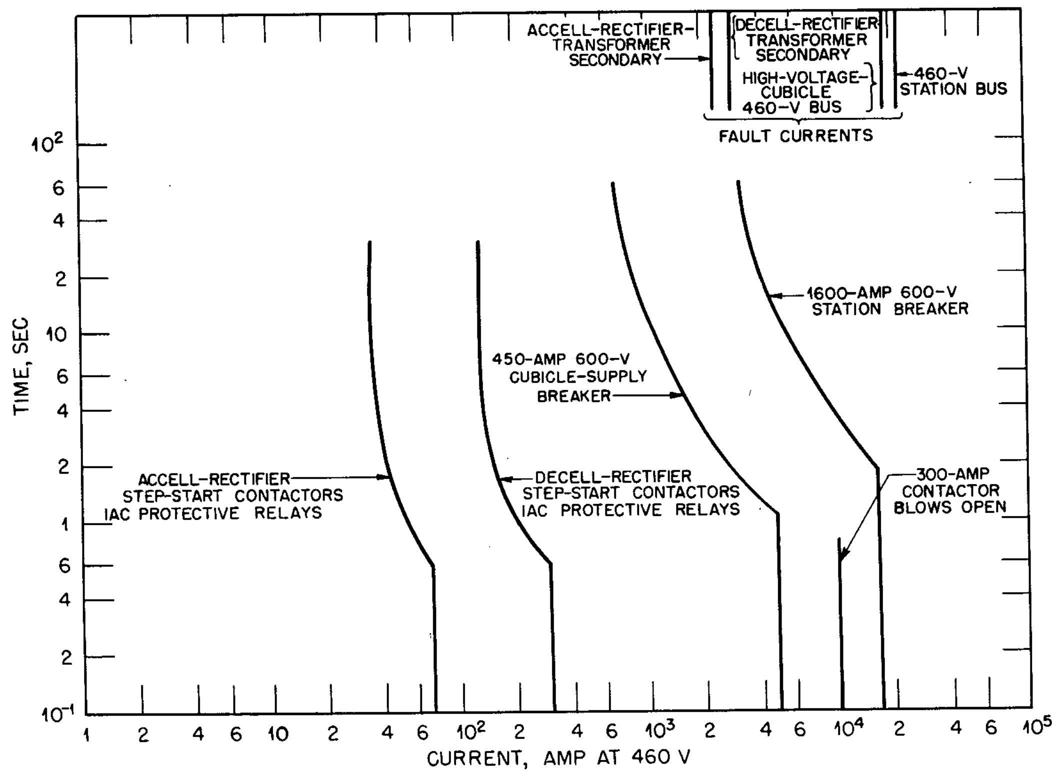


Fig. 6.12 — Typical relay coordination curve in Alpha II. Note that curves indicate the time required for the contactors and breakers to open.

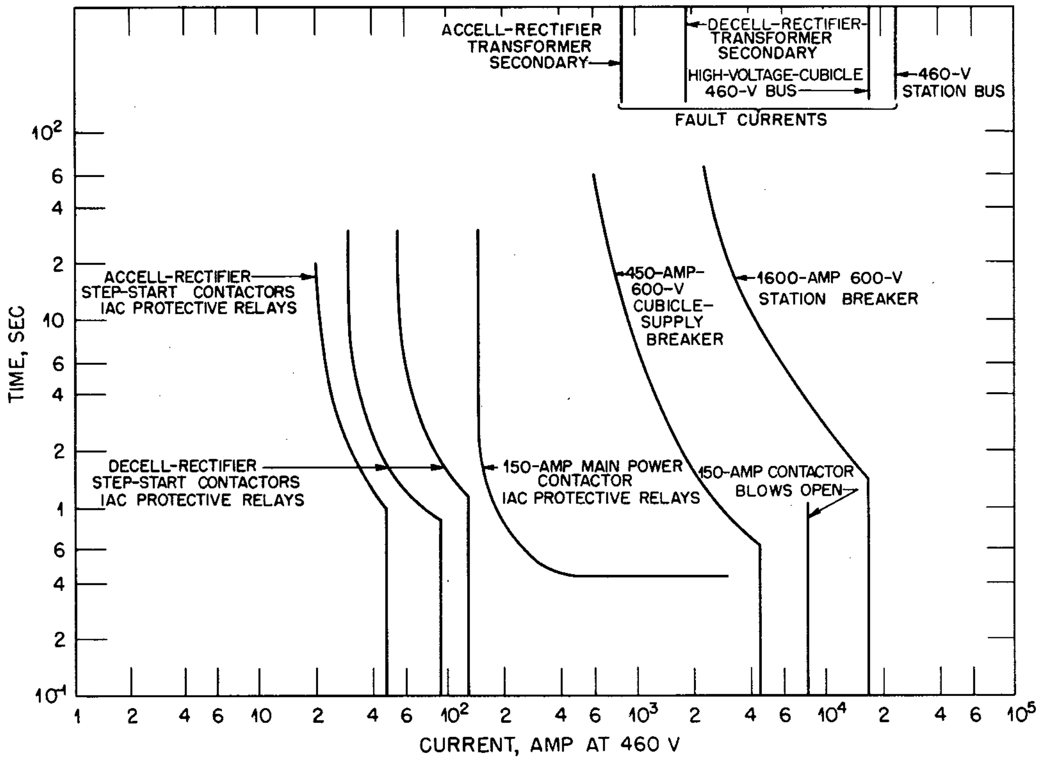


Fig. 6.13 — Typical relay coordination curve in Beta. Note that curves indicate the time required for the contactors and breakers to open.

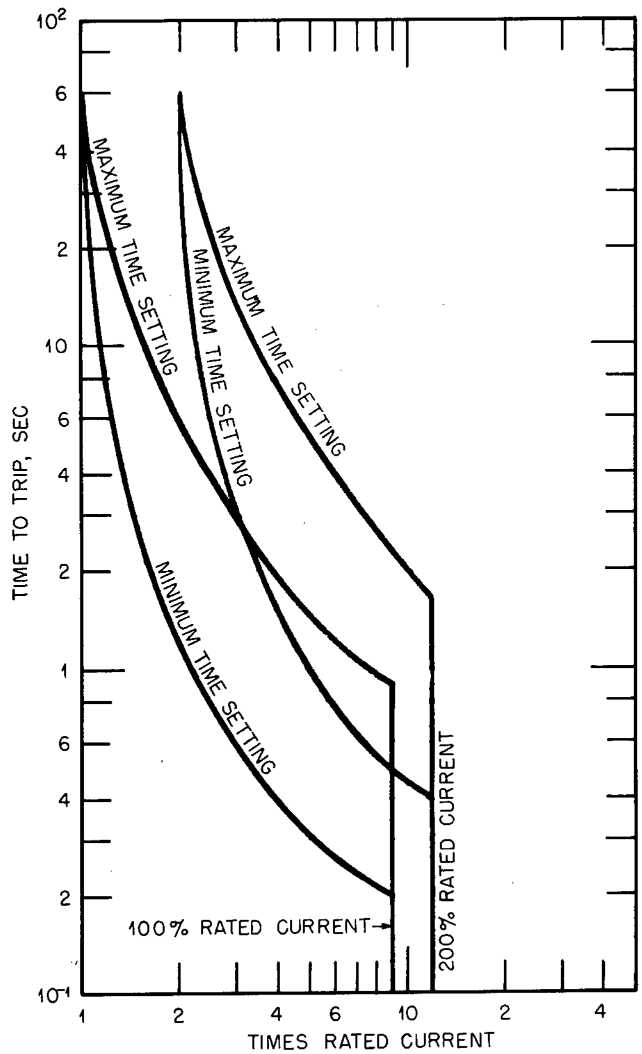


Fig. 6.14—Approximate time-current characteristic curves for the dual magnetic-tripping device.

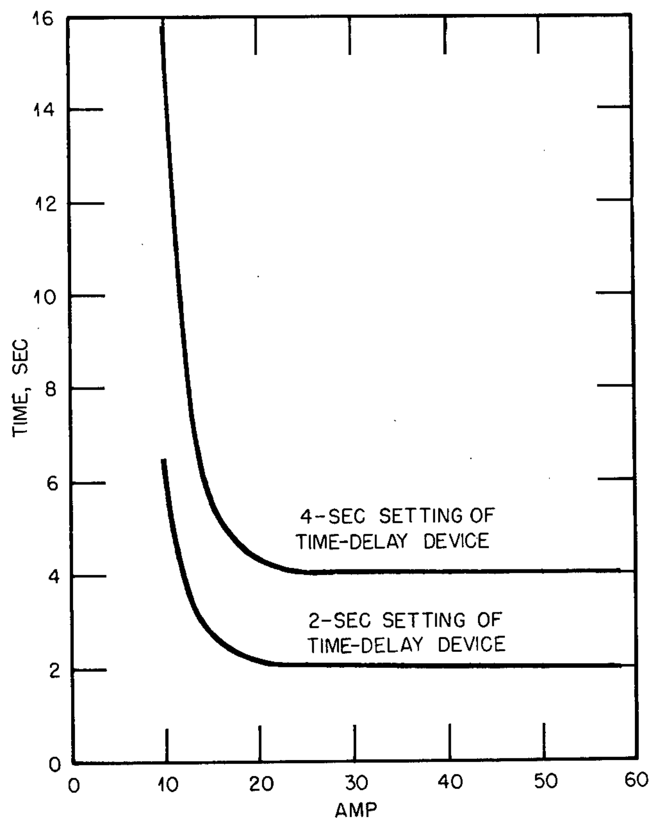


Fig. 6.15—Approximate time-current characteristic curves for 5-amp relay coil set for 8 amp in General Electric PAC relay.

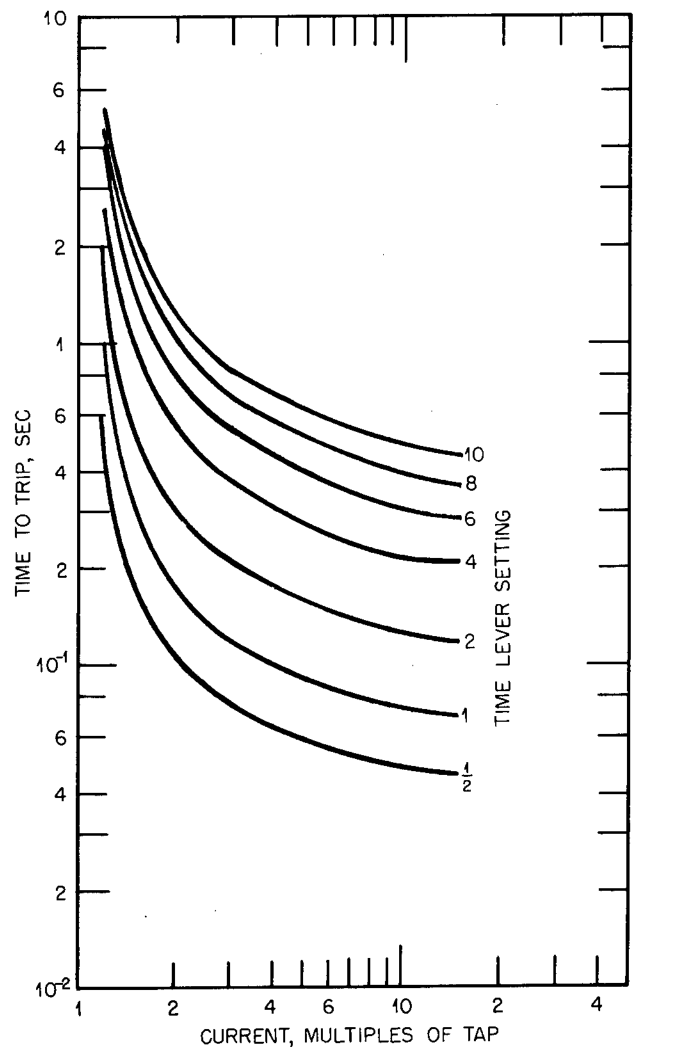


Fig. 6.16—General Electric IAC relay induction time element, approximate time-current characteristic curves.

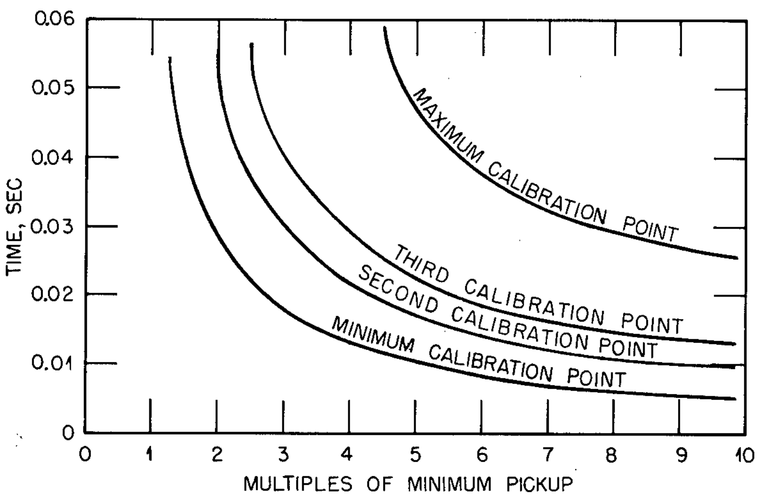
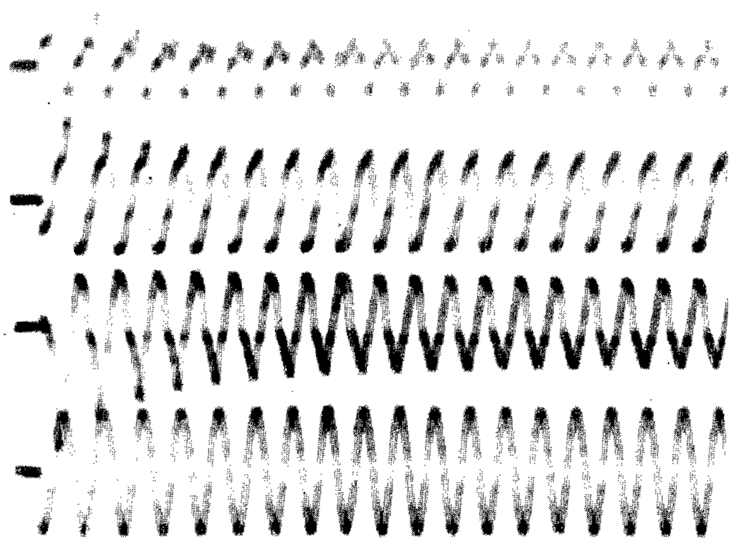
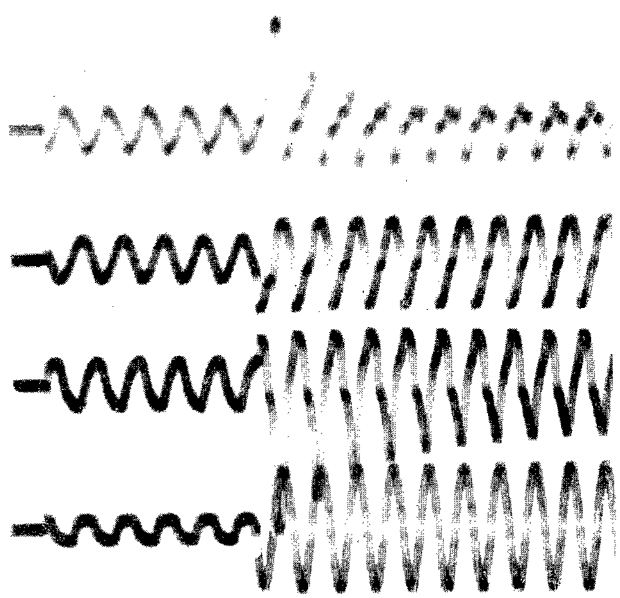


Fig. 6.17—General Electric IAC relay instantaneous element, approximate time-current characteristic curves.

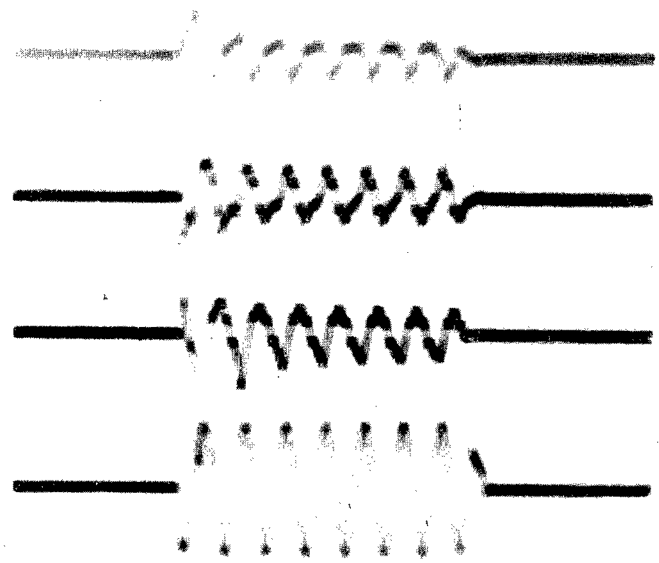


(a)

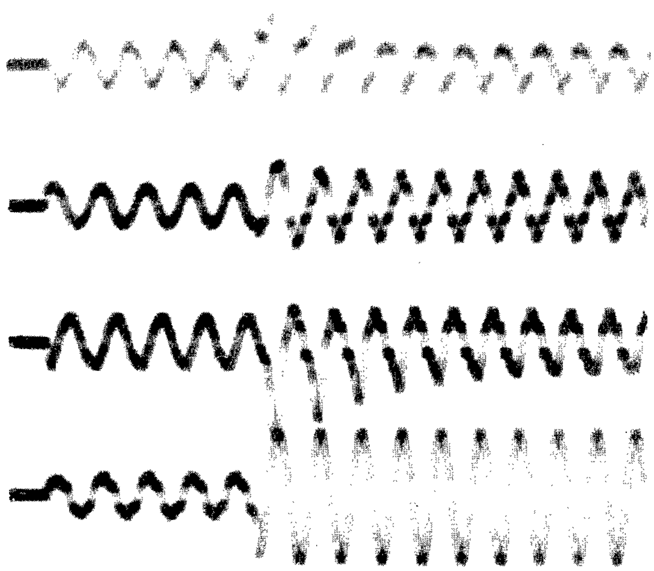


(b)

Fig. 6.18—Alpha II decell-rectifier inrush-current oscillograms. (a) Without step-start equipment. (b) With step-start equipment. (See Table 6.3 for details.)



(a)



(b)

Fig. 6.19—Alpha II decell-rectifier inrush-current oscillograms. (a) Without step-start equipment. (b) With step-start equipment. (See Table 6.3 for details.)

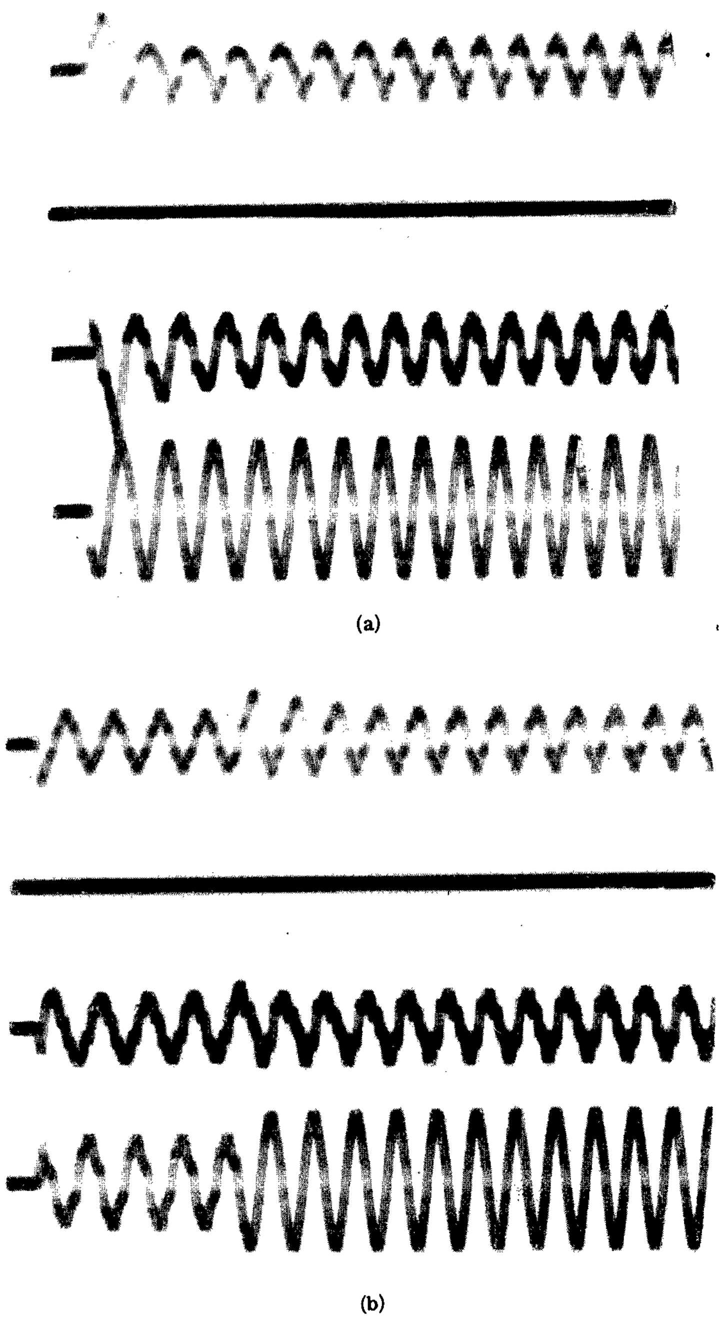
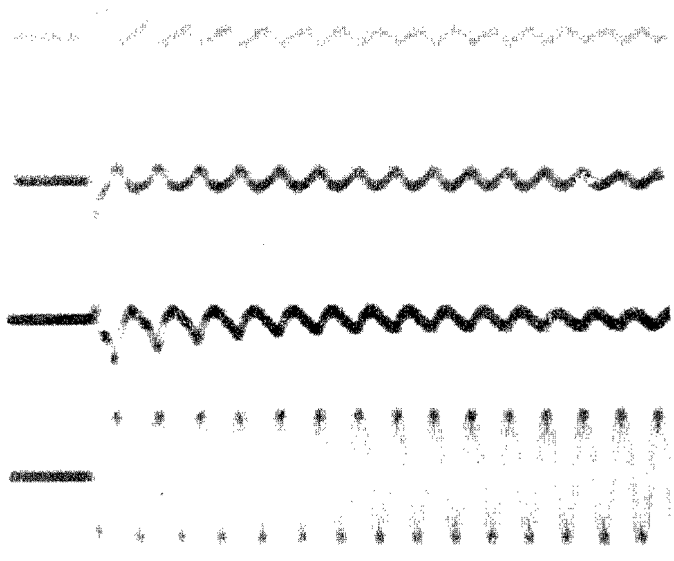
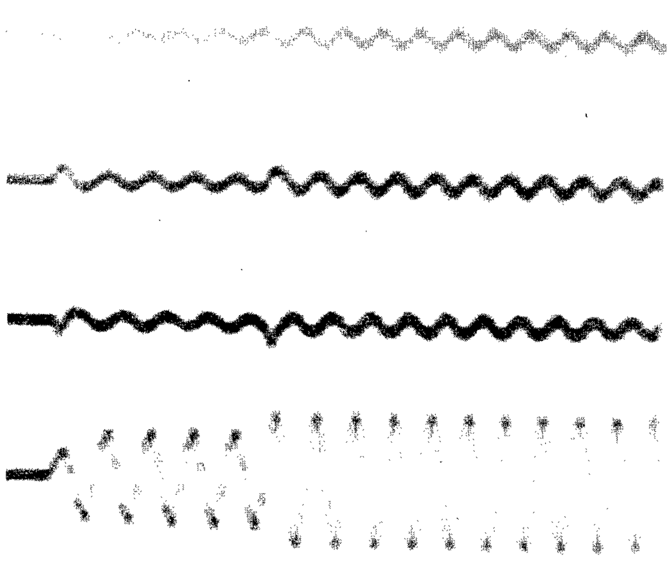


Fig. 6.20—Alpha II accell-rectifier inrush-current oscillograms. (a) Without step-start equipment. (b) With step-start equipment. (See Table 6.3 for details.)

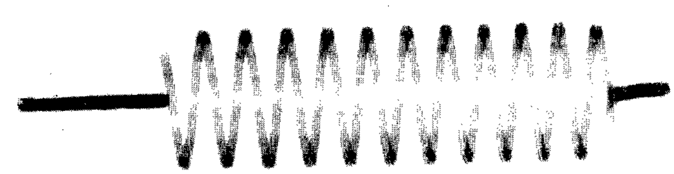


(a)

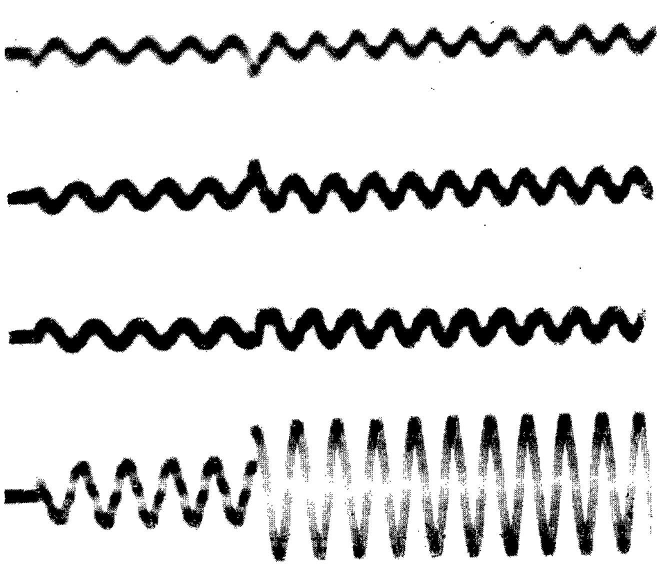


(b)

Fig. 6.21 — Alpha II accell- and decell-rectifier inrush-current oscillograms. (a) Without step-start equipment. (b) With step-start equipment. (See Table 6.3 for details.)



(a)



(b)

Fig. 6.22 — Alpha II accell- and decell-rectifier inrush-current oscillograms. (a) Without step-start equipment. (b) With step-start equipment. (See Table 6.3 for details.)

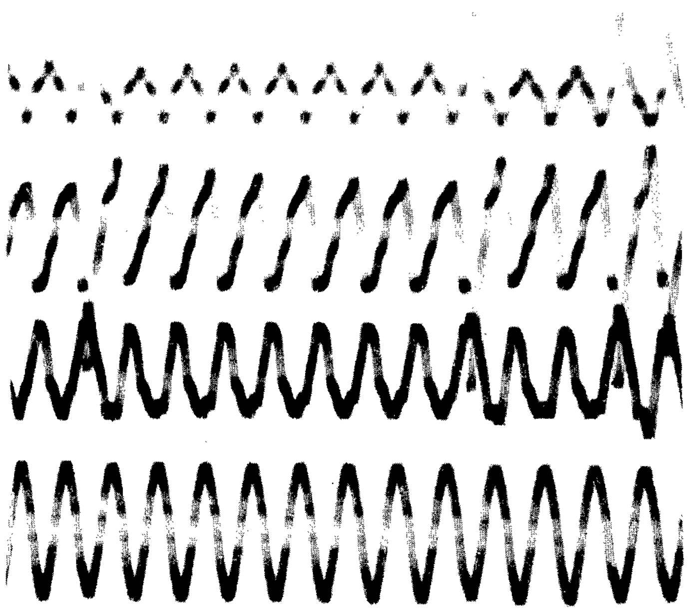


Fig. 6.23 — Alpha II decell-rectifier gas-kick-current oscillograms. (See Table 6.3 for details.)

Chapter 7

DECELL-SUPPLY ELECTRONIC REGULATOR

In the general description of the mass-spectrograph channel (Chap. 1) it was pointed out that the degree of voltage regulation that could be obtained from a simple filtered rectifier power supply was not adequate for use with this equipment. It was further stated that a losser electronic regulator was used to stabilize the decell voltage and to reduce variations of this voltage to less than 1 part in 2,500. The type of regulator used in the CEW-TEC plant will be discussed in detail below.

Figure 7.1 is a block diagram of the regulator scheme employed. This figure shows the functional arrangement of the filtered high-voltage rectifier, the load, the two sampling resistors R_1 and R_2, the d-c amplifier, and the losser regulator tube V_1.

The operation of such a regulator can be explained by a simplified schematic diagram, such as Fig. 7.2. The regulator is a voltage-regulated d-c high-voltage supply feeding a variable load and consisting of the following major items: high-voltage rectifier, resistance-capacitor filter, voltage divider, voltage standard, d-c amplifier, regulator tube, and high-voltage-rectifier load.

It should be remembered that the decell high-voltage rectifier and filter, previously described in Chap. 2, Sec. 2, give a d-c output voltage containing a ripple component that is in excess of that which can be tolerated for this particular application. Such a rectifier and filter have poor regulation because of line-voltage changes and high internal impedance. The output voltage of such a rectifier and filter combination can be controlled by means of a variable series resistance to compensate for supply-line voltage changes and variation in load current.

In an electronic voltage-regulator system the variable-resistance element mentioned above is replaced by an electronic vacuum-tube triode. The equivalent resistance of the triode is controlled by its grid-to-cathode voltage. Any changes in the load voltage can then be made to change this equivalent resistance automatically by changing the regulator-tube bias. However, before small changes in load voltage can

be compensated and applied to the grid of the regulator tube they must be amplified. There is little delay in changing the equivalent series resistance offered by the regulator tube because an electronic amplifier having a very short time delay can be constructed.

When the voltage divider consisting of the two resistors R_1 and R_2 (Fig. 7.2) is connected across the load, a voltage proportional to the ratio $R_2/(R_1 + R_2)$ occurs across R_2. The steady-state portion of the load voltage appearing across R_2 is counteracted by a stable standard voltage B_1. Owing to the use of the standard voltage, only the change in load voltage appearing between points 1 and 2 is applied to the input of the d-c amplifier. The phase relation of voltage changes appearing across R_2 is such that an increase in load voltage, when amplified by the d-c amplifier, increases the bias of the regulator tube and thus increases its equivalent resistance. The d-c amplifier ordinarily used is of the high-gain type. Therefore very small changes of grid voltage on V_3 result in large changes in the bias voltage and equivalent resistance of V_1. Thus changes in voltage across resistance R_2 are compensated so that the voltage across R_2 is returned to a value equal to the standard voltage.

An increase in the regulator-tube equivalent resistance causes a higher voltage to appear across the regulator tube, which in turn exactly compensates for an increase in voltage at the output of the rectifier filter. A change in load current due to the internal impedance of the power supply causes a change in output voltage, which in turn alters the equivalent internal resistance of the regulator tube, thus causing the load voltage to return to its original value. Therefore an electronically regulated high-voltage supply can be made to have an over-all internal impedance approaching zero.

The stability of such a regulated high-voltage supply depends chiefly on a highly stable standard voltage and on the amplifier gain. The stability of a regulator system is dependent on the standard voltage because it is not included in the regulating loop. Therefore changes in value of the standard voltage appear in the regulated output directly as the ratio of the output to the standard.

Any changes in the characteristics of performance in the regulating loop, except amplifier gain, affect the regulated output by the ratio $1/(1 + AB)$, where A is the amplifier gain and B is that portion of the output fed back to the input. Usually the B term is a resistance device and consequently very stable. From the ratio $1/(1 + AB)$ it is obvious that the stability of the system is impaired by any decrease in amplifier gain due to the aging of tubes, etc.

Representative photographs (Figs. 7.3 and 7.4) show the arrangement of the component parts of the decell voltage regulators used in connec-

tion with the decell high-voltage supplies. Complete schematic diagrams of the decell voltage regulators originally supplied are shown in Figs. 7.5 to 7.8.

In the operation of this equipment it was found desirable to operate the regulator tubes thermionic-emission-limited for currents slightly higher than the normal load current. The term "thermionic-emission-limited" indicates that the flow of electrons from the cathode to the anode, rather than being limited by the space-charge effect, is limited by the number of electrons emitted from the cathode as determined by operating temperature. Therefore a thermionic-emission-limited tube will have a constant anode current for increasing anode voltage, and a tube operating under such a condition when placed in series with a variable-current load will have a low internal voltage drop for currents up to the emission-limit point. After the emission-limit point has been reached, the rectifier and limiter will perform as a constant-current source. Emission-limiting was a decided convenience in plant operation because (1) when an arc occurred at the load it prevented high current requirements from being placed on the rectifier equipment and (2) by limiting the current supplied to the load it minimized the damage to the load equipment due to such arcs. The desired emission-limit value was therefore only slightly above the value of the normal operating current so that when shorts occurred at the load the fault current would not exceed the rating of the rectifier equipment.

If the anode current is plotted as a function of the applied anode voltage for a diode or triode tube, it will be found that the anode current increases gradually with increasing voltage up to a point at which thermionic emission-limiting has been reached. At this point it will be found that the voltage increases rapidly with a very small increase in anode current. In the use of a limiter tube in plant equipment the ratio between the current at which thermionic emission-limiting started and the maximum current for full applied rectifier voltage was important in determining the proper values for setting the protective relays. Since this ratio determined the maximum fault current, it was a figure of merit for a limiter tube used for plant operation and was known as the "cutoff ratio" for the tube. The GL-893 supplied for plant operation by General Electric had a cutoff ratio of approximately 1.45. This cutoff ratio is best illustrated by the curve in Fig. 7.9. In this figure, point A is the point at which thermionic emission-limiting starts, and point B represents maximum anode current for full applied rectifier voltage. Therefore the ratio B/A is the cutoff ratio.

Special designs were made for limiter tubes in plant operation by various manufacturers in an effort to secure a tube with the minimum

cutoff ratio. Experimental models were built in which this ratio had been decreased to 1.1. Such a tube is described more fully in Chap. 9, Sec. 2.

In this discussion it should be remembered that during the installation of equipment in the plant it was found desirable to make changes and improvements in the regulator, as indicated by experience during operation. The changes covered in this section will be only those made by General Electric Company on these regulators prior to the time that they were turned over to CEW-TEC for operation.

1. VOLTAGE DIVIDER

The voltage divider used in conjunction with the electronic regulator furnished to the d-c amplifier a sample of the high voltage being regulated. The ratio of the two sections of the divider was such that, in conjunction with the range selector, the sample supplied to the d-c amplifier was approximately equal to the standard voltage. In the equipment supplied the actual values of the two sections of the divider were 17 megohms and 246,400 ohms with tolerances of 0.25 per cent.

Owing to the transient nature of the load on the regulated voltage supply, the voltage divider had to be capacitatively compensated so that its transient response would provide satisfactory voltage recovery after a spark at the load had occurred. The voltage recovery time after a spark had occurred at the load had to be fast enough so that the ion beam would not remain on the U 235 receiver pocket long enough to contaminate the pocket appreciably. Furthermore, on recovery the voltage could not overshoot the desired value by an appreciable amount, or a recurrence of the tank spark would take place. The necessary capacitance to shunt the 17-megohm section of the voltage divider was provided by the capacitance between an internal shield and the voltage-divider case for the Alpha II and Beta equipment. Because the positive high-voltage lead was grounded in the Alpha I equipment, an additional shield that was at 35 kv negative with respect to ground and the divider case was required between the resistor shield and the grounded case. The low-resistance section of the voltage divider was shunted by an external mica capacitor.

In the Alpha I equipment the low-resistance section of the voltage divider was essentially at ground potential. The voltage-divider terminals were brought out through two spark plugs mounted near the bottom of the voltage-divider case. The third terminal for the high-resistance section of the divider was brought out through a standoff insulator through the bakelite cover of the divider case. This was necessary

because the high-resistance section was connected to the negative side of the high-voltage supply.

In both the Alpha II and Beta equipment the polarity of the high-voltage supply with respect to ground was opposite to that in the Alpha I equipment. This required one end of the 17-megohm section of the voltage divider to be at ground potential and the 246,400-ohm resistor leads to be brought out through standoff insulators mounted on the bakelite cover of the divider case.

Drawings and photographs of the voltage dividers used are shown in Figs. 7.10 to 7.19.

2. ELECTRONIC REGULATOR

The decell voltage-regulator amplifier and voltage standard and the necessary d-c power supplies for the operation of this equipment were built on an 11- by 17- by 3-in. chassis.

Four different types of regulators were supplied as original equipment, the schematic diagrams of which are shown in Figs. 7.5 to 7.8.

The amplifier power supply used in the Alpha I and Beta regulator 1 (Fig. 7.5) consisted of two separate transformers together with their respective rectifiers and filters, one rectifier being electronically regulated. A stable reference voltage of 300 volts was obtained from two VR-150-30 glow-discharge tubes connected in series. A 6SH7 tube was used as a d-c amplifier controlling a 6L6 series regulator tube. This regulated voltage was held at 500 volts, which was the standard voltage used in conjunction with the divider described in Sec. 1 to give a regulated power-supply voltage range of 23 to 35 kv. In the Alpha II and also the Beta type 2 regulators (Figs. 7.6 and 7.7) the same type of regulated power supply was used except that the two transformers described above were combined into a single transformer with both secondary windings on the same core. In the Beta regulator 3 (Fig. 7.8), only one power-supply rectifier and filter combination was used. The reference voltage in this case consisted of four VR-75-30 glow-discharge tubes connected in series. This standard voltage was the reference used in maintaining a 530-volt regulated supply to the d-c amplifier, which was a 6SH7-6L6 tube combination.

The main d-c amplifier, in all except Beta regulator 3, consisted of a 2-stage d-c amplifier with a 6AG7 input tube driving an 807 tube in the output stage. In the Beta regulator 3 the tube complement consisted of a 6SC7 tube for the input stage and an 807 tube for the output stage.

The Alpha II and Beta type 2 regulators had a capacitor-resistance negative-feedback connection between the plate of the 807 and the cathode of the input tube. In series with the input lead there was inserted

a capacitor-resistance combination that was used to alter the transient response of the amplifier. In the regulators shown in Figs. 7.5 and 7.6 the 6AG7 plate load did not consist of a pure resistance but was compensated for high-frequency response. The grid of the 807 tube in Figs. 7.6 and 7.7 was connected to the plate of the input stage of the amplifier through a capacitor-resistance combination that affected the recovery time of the regulator system for load transients.

In the regulators having two power supplies the electronically regulated negative-supply terminal was connected to a tap on the voltage divider of the second supply. This connection was necessary in order to obtain proper voltage for operation of the d-c amplifier and was intended to give a grid-bias range of from −300 to +300 volts for the regulator tube. However, the plate-load resistance of the 807 tube was so high that sufficient current could not be supplied to the grid of the regulator tube in the positive region, and consequently the grid voltage of the regulator was never driven more than a few volts positive.

A meter was supplied to indicate the operating range of the regulator. This range meter was a General Electric DO-58 0-30 full-scale milliammeter and was to read the plate current of the 807 tube. The readings gave an indication of the grid bias applied to the regulator tube. By means of this range meter it was possible to adjust the output of the high-voltage rectifier supply by means of its induction voltage regulator to such a value that the d-c bias supplied to the grid of the regulator tube would fall within the operating range of this tube.

Owing to the operating voltage and operating load current and to the transient nature of the load it was necessary to use a main regulator tube having high forward voltage, inverse voltage, and anode dissipation ratings. For this reason the General Electric GL-893 triode was used as a regulator tube. It should be pointed out that when the regulator tube was used under emission-limiting conditions the full output of the rectifier was dissipated by the tube. During sparking the load voltage fell to essentially zero, and the rectifier load current was limited only by the emission-limit setting of the regulator tube, and a large portion of the energy stored in the high-voltage rectifier filter was dissipated in the regulator tube.

The GL-893 had the following electrical and physical characteristics. It was a water-cooled triode with a 6-phase star-connected tungsten filament rated at 10 volts and 61 amp per strand, using the standard 3-phase filament connection. This tube had an amplification factor of 36. Its maximum ratings were as follows:

Regulator operation:	
1. Peak forward plate voltage, kv	20
2. Average plate dissipation, kw	20
3. Peak plate dissipation, kw	20
4. Maximum negative grid voltage, volts	1,000
Surge-limiting operation (emission-limiting):	
1. Peak forward plate voltage, kv	40
2. Peak plate current, amp	7.5
3. Average plate dissipation, kw	20
4. Peak plate dissipation, kw	40
5. Duration of surge if plate dissipation exceeds 20 kw, sec	2

The tube had a water-cooled copper anode 0.090 in. in thickness and 3³⁄₁₆ in. in diameter. It required a cooling-water flow of 15 gal per minute. The maximum diameter of the glass envelope was 6 in., and the over-all length was 26¾ in. Filament connections were made to studs on a circular insulating board covering the filament end of the glass envelope.

Characteristic curves for this tube are given in Fig. 7.20. Figure 7.21 is a photograph of this tube.

In the Alpha I high-voltage supply it was necessary to furnish a separate limiter tube. A separate limiter tube was needed because the Alpha I high-voltage rectifier used a double Y with interphase transformer connection and the GL-893 regulator tube was on the grounded side of the supply. If the regulator tube had been emission-limited during operation, the potential of the rectifier to ground would have changed by an amount essentially equal to the high-voltage rectifier output or 35 kv whenever sparking occurred at the load. When the system was tried, prior to the installation of Alpha I cubicles at the plant site, it was found that this condition introduced into the high-voltage rectifier transients of such a high order of magnitude that it was impossible to operate the equipment. As a result a diode was used in the ungrounded line from the rectifier, this diode being operated emission-limited, and the GL-893 regulator tube was operated with a filament voltage that gave an emission equal to several times the emission-limiter tube. The limiter tube used in the Alpha I equipment was a General Electric type GL-562. This tube was identical with the GL-605, which was described in Chap. 2, Sec. 2. This was also the same tube used for rectifier service in the Alpha II decell rectifier. The only difference between the GL-562 and the GL-605 was that the GL-562 tubes were test-selected from a group of GL-605 tubes at the factory.

The 836 high-vacuum low-drop diode tube was connected between the GL-893 grid and cathode to prevent the grid of the GL-893 from being driven positive.

The 836 tube had the following characteristics. It was a high-vacuum radiation-cooled diode, having an indirectly heated cathode. The tube had a maximum diameter of 2 7/16 in. and a maximum seated height of 6 in. The filament was single phase rated at 2.5 volts and 5.0 amp. The tube had a peak inverse plate voltage rating of 5 kv and a peak plate current of 1.0 amp. The average plate-current rating was 0.25 amp. A characteristic curve for this tube is given in Fig. 7.22.

The use of the 836 tube was necessary to prevent a so-called "run-away" condition of the GL-893 grid voltage that otherwise would occur during emission-limiting. When the grid of the GL-893 became slightly positive, the grid voltage had a tendency to increase, giving much the same results as the effect produced by reverse grid current through a high-resistance grid return in an ordinary power tube. The 836 was therefore connected between the grid and filament of the GL-893 to prevent the grid of the GL-893 from being driven positive.

In all buildings except the last Beta building the 836 tube was mounted near the GL-893, and the 836 tube heater voltage was supplied through a series resistor from one leg of the GL-893 filament circuit. In the last Beta building the 836 was located on the main d-c amplifier chassis, and its heater power was supplied by an additional winding on the amplifier power transformer.

The regulated high-voltage range selector consisted of a coarse and fine voltage control. The coarse control was a decade type having increments of 1.0 kv. The fine control was a continuously variable type, having two rheostats connected in tandem in such a manner that the resistance of one increased as the other decreased, thus maintaining a constant value of resistance in the circuit. This fine control covered a range of 1.3 kv. The range selector consisted of a voltage divider connected across the 500- to 525-volt standard voltage. The selected portion of the 500- to 525-volt standard, as determined by the range selector, was made equal to the voltage across the 246,400-ohm section of the voltage divider by the operation of the electronic regulator. Because the high-voltage output of the regulated power supply was proportional to this voltage, it could therefore be maintained at any desired value between 23 and 35 kv by selecting a suitable portion of the standard voltage by means of the range selector. Figure 7.23 shows the relation between standard voltage, range selector, and voltage divider.

In order to check the operation of the regulated decell supply a Du Mont 164E oscilloscope was connected to its output to be used as a

monitor. This oscilloscope was used by the operator to check the ripple on the decell voltage supply and to assure him that the regulator was operating properly at all times. The voltage divider for the oscilloscope consisted of a 0.001-μf high-voltage isolating capacitor, a 1,000-ohm series protective resistor, and a 2-megohm signal resistor. The ripple component of the high-voltage supply appearing across the 2-megohm resistor was fed to the input terminals of the oscilloscope. This combination was calibrated in terms of peak-to-peak ripple volts.

3. BEAM-CONTROL REGULATOR

The purpose of the beam-control regulator, as supplied, was to maintain the U 235 ion-collecting electrode current at a constant value. This was done by using the output of the beam-control regulator to change the voltage appearing across the high-voltage divider, thus causing a decell voltage change and, in turn, a change in the position of the ion beam on the collector electrode. As was previously pointed out, the current through the high-voltage divider was held constant by the main voltage regulator. Thus any change in the voltage appearing across the voltage divider would produce a voltage change in the regulated high voltage owing to the action of the electronic regulator in maintaining a constant current in the voltage divider.

The block diagram of Fig. 7.24 shows the manner in which the beam-control regulator output was connected between the negative high voltage to the load and the negative end of the voltage divider R_1-R_2. The input signal to the beam-control regulator was derived from the ion-beam currents received by the two collecting electrodes.

From Fig. 7.25 it may be seen that the beam-control regulator consisted of essentially four parts, namely (1) a signal selector that automatically selected the most favorable ion-collecting electrode signal and used it to control the decell voltage, (2) a d-c amplifier that amplified the signal from the collecting electrode, (3) a variable-resistance tube controlled by the d-c amplifier, and (4) an indicator that showed when the variable-resistance output tube was on a usable portion of its range. A switch S_1 was provided to make the beam-control regulator inoperative until needed.

Referring to Fig. 7.26, the operation of the regulator was as follows: Terminal point 4 was connected to an ion-collecting electrode. The voltage drop across the rheostat R_1 was held nearly equal to the standard voltage B_1 by the regulating action of the system, which gave points 4 and 6 essentially the same potential. Likewise the voltage drop across R_2 was nearly equal to B_1, and thus point 5, which was connected to a second ion-collecting electrode, was essentially at the same potential as point 6. A small difference of potential between points 4 and

6 constituted a signal for the tube V_1. A corresponding signal was applied to the tube V_2 from the second collecting-electrode channel input at point 5. Owing to the signal voltage on V_1, its plate potential decreased, and, when it dropped below the plate potential of V_3, the largest portion of the plate current for V_1 flowed through resistors R_5, R_6, and R_7. The values of the resistors R_3 and R_4 were large compared with the values of R_5, R_6, and R_7. The voltage across the resistors R_5, R_6, and R_7 due to the plate current of V_1 supplied a grid signal for the output tube V_4. The input tube V_2 controlled the output tube in the same manner as described above for input tube V_1. However, only one of the two tubes V_1 and V_2 controlled V_4 at any instant. Thus V_1, V_2, and V_3 constituted a d-c amplifier and signal selector to control the output tube V_4. The ion-collecting-electrode current control was thus determined by the plate potentials of tubes V_1 and V_2. The larger of the two ion currents controlled the output tube V_4.

The grid-voltage signal on the output tube V_4 was indicated by a magic-eye tube V_5. This voltage was controlled by the voltage divider consisting of resistors R_5, R_6, and R_7. The resistor R_6 was adjustable, thus providing an indication that tube V_4 was operating in the proper grid-voltage range.

The magnitude of the collecting-electrode current was determined by the resistance values of R_1 and R_2, these two resistors being of the same value. The regulator maintained the collecting-electrode current at a value that, when multiplied by the resistance of its respective control rheostat, was equal to the reference voltage B_1. This was accomplished by an adjustment of the regulated high-voltage supply in such a direction as to swing the ion beam off the collecting electrode to a sufficient degree to give the desired electrode current. The complete schematic diagram of the original beam-control regulator, as supplied for Alpha I, is shown in Fig. 7.27.

4. DECELL-VOLTAGE-REGULATOR SERVICE CONDITIONS

In a previous discussion of the high-voltage channel it was explained that a voltage regulation of 1 part in 2,500 was required for the decell voltage. Since the actual decell operating voltage was approximately 39 kv, this meant that the ripple component of this voltage could not exceed 14 volts. With the electronic voltage regulator described in Chap. 8, Sec. 1, it was found during plant operation that the average ripple on the decell voltage was of the order of 215 volts, peak to peak. The oscilloscope mounted in the high-voltage cubicles was used as a means of monitoring the decell voltage to ensure that this ripple value would never exceed the theoretical maximum of 14 volts, and this was

used as a criterion for the removal and repair of the decell regulator.

The average regulated d-c voltage for plant operation was approximately 39 kv. The average load current for Alpha I was 0.80 amp, that for Alpha II was 1.95 amp, and that for Beta was 0.55 amp. Owing to the cutoff ratio of the limiter tubes used it was necessary to establish the emission-limit setting at 150 per cent of these values. This meant that during sparking at the load the Alpha II and Beta regulator tubes were required to be capable of handling a peak plate dissipation of 57 and 32 kw, respectively. These tubes were actually rated for a peak plate dissipation of 60 kw, and, since in Alpha II two such tubes were operated in parallel, these tubes were not overloaded. In Alpha I the regulator tube was not required to act as an emission limiter since a separate limiter tube was supplied in this circuit. However, the 562 limiter tube had a peak plate dissipation equal to that of the regulator tube, and, although it was required to dissipate 47 kw, its peak plate dissipation was not exceeded. In the case of both the regulator and limiter tubes their nominal peak plate-voltage rating exceeded that which they were required to withstand in the operating circuit.

In the case of the d-c amplifier none of the circuit components were actually overloaded, although certain resistors did overheat. This condition was due to the location of this amplifier, which was such that proper ventilation for these resistors was not secured. The condition was corrected, as explained in Chap. 8, Sec. 1, by moving certain circuit components and by providing more adequate ventilation.

The specification for the beam-control regulator required that this regulator automatically control the output voltage of the decell regulator in such a manner as to maintain the greater of the two ion currents to the U 235 collector electrode to within plus or minus 5 per cent of the value selected by the channel operator. The Alpha I regulator had been designed to control 15 ma, and the Alpha II regulator had been designed for 10 ma. For both regulators the actual values of operating currents fell within the range of the regulators.

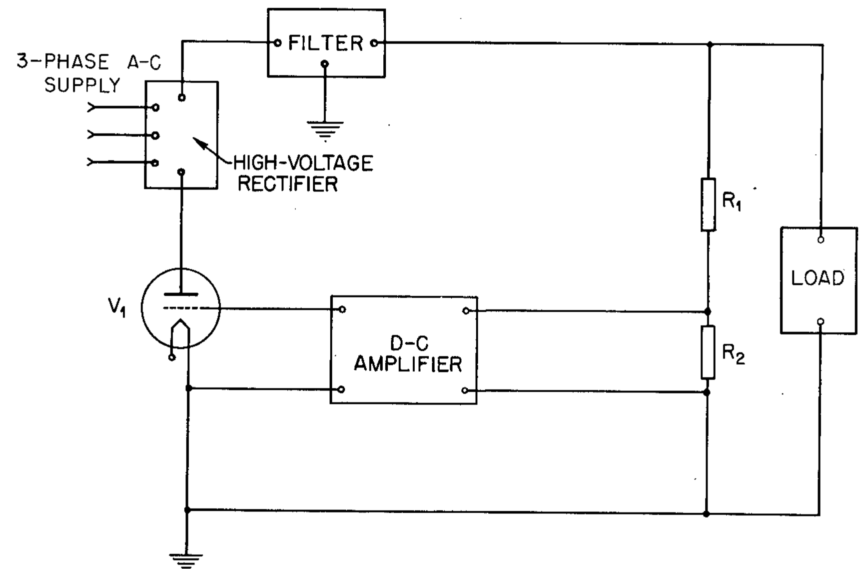


Fig. 7.1—Block diagram of high-voltage d-c electronic-regulator system.

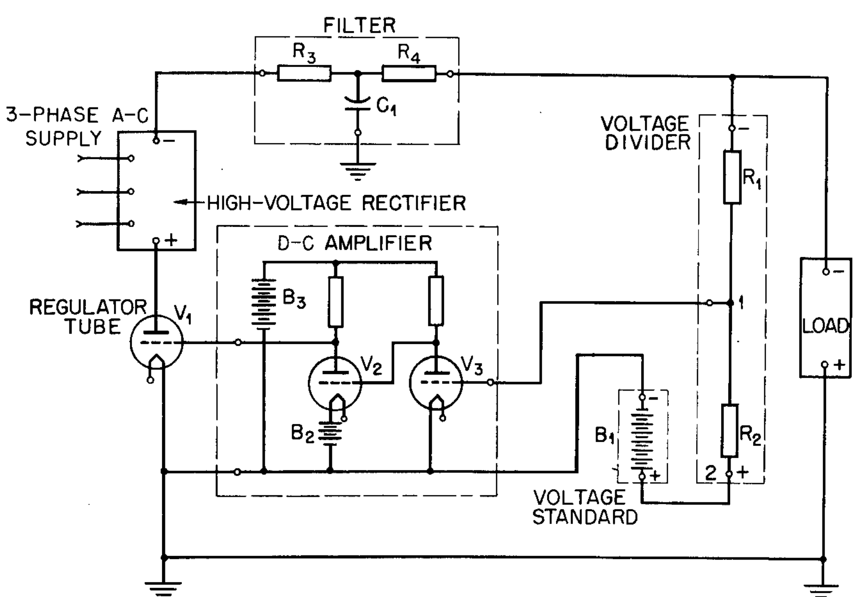


Fig. 7.2—Simplified schematic diagram of high-voltage d-c electronic-regulator system.

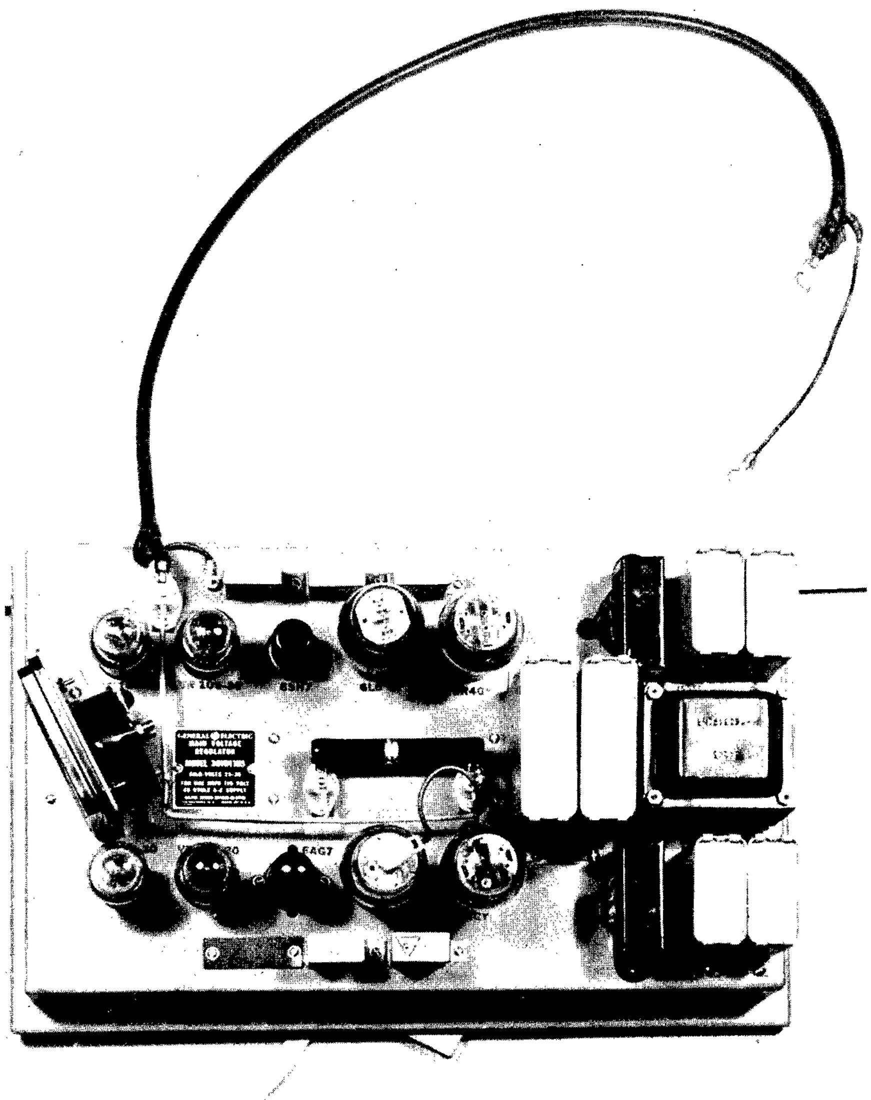


Fig. 7.3 —Representative decell voltage regulator.

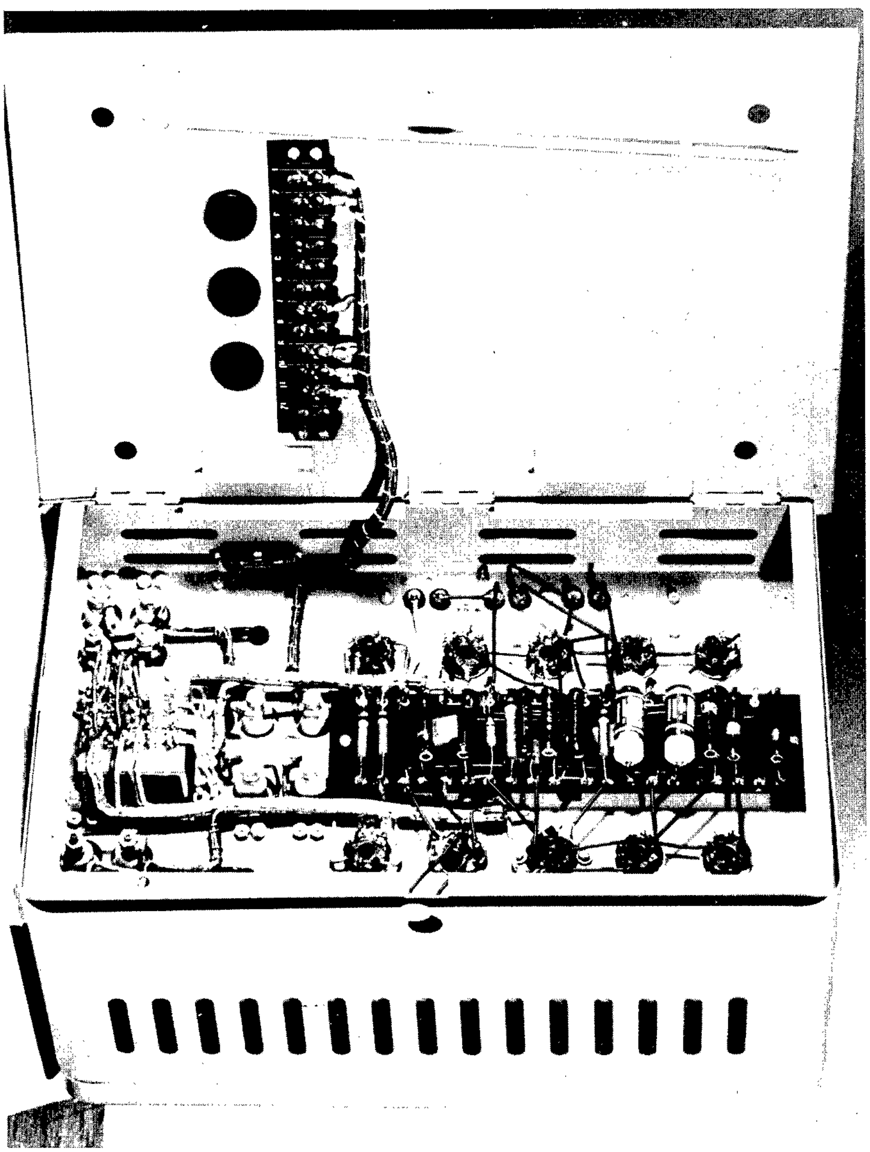


Fig. 7.4—Representative decell voltage regulator.

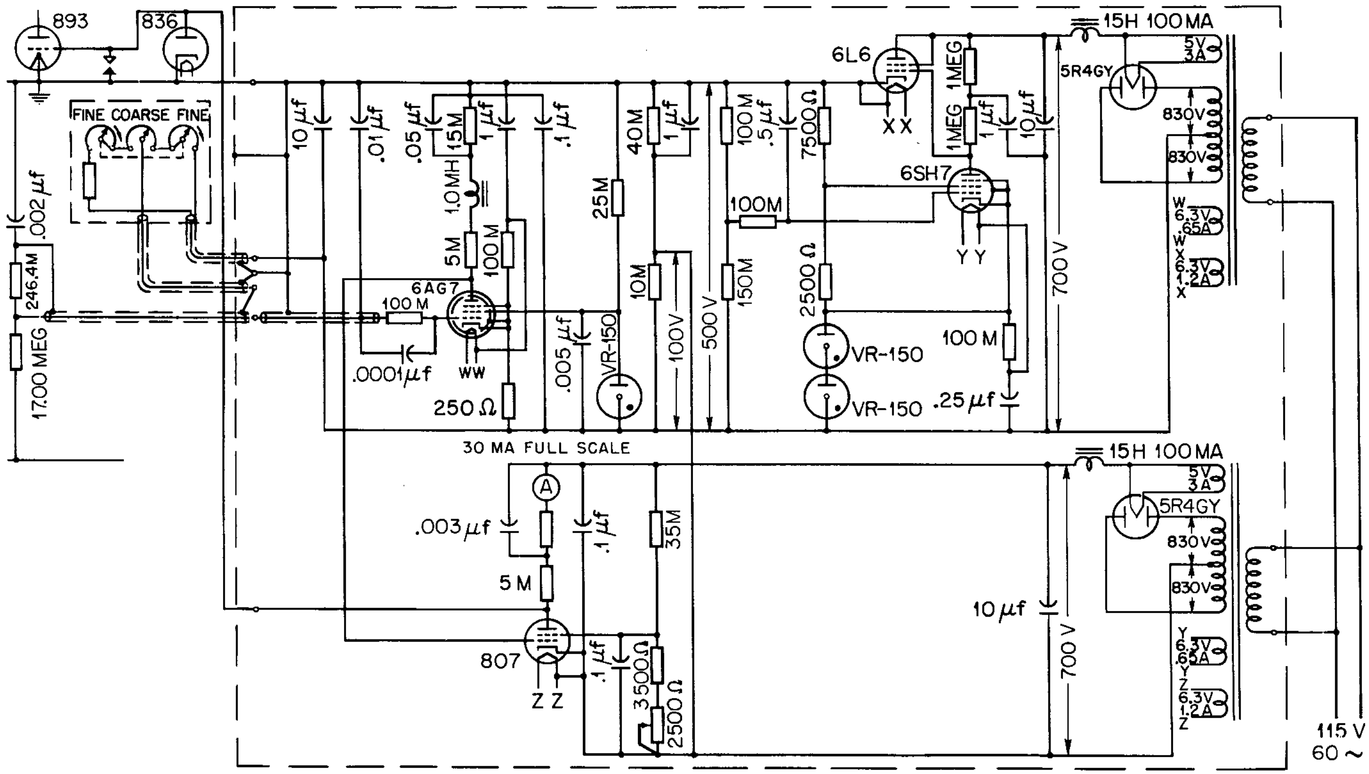


Fig. 7.5 — Schematic diagram of Alpha I and Beta (type 1) decell voltage regulator.

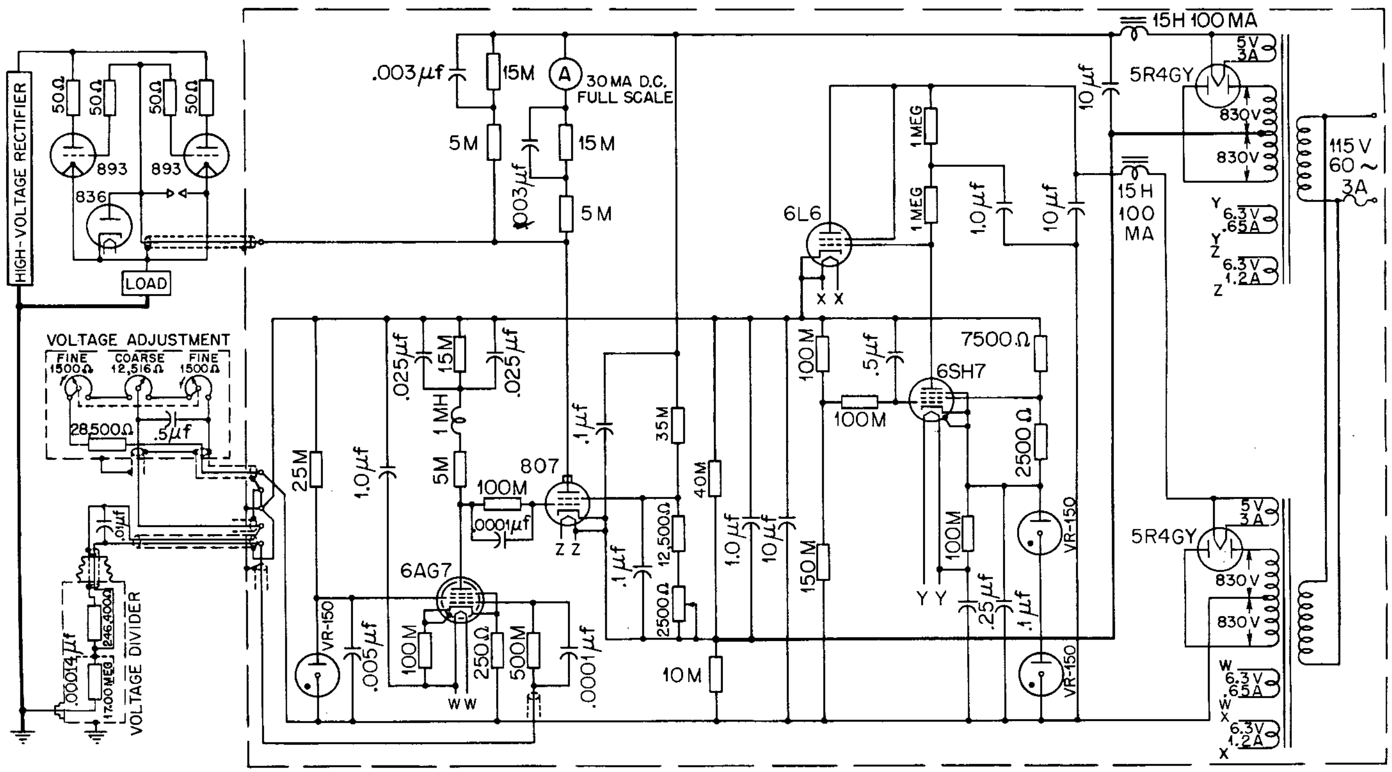


Fig. 7.6 —Schematic diagram of Alpha II decell voltage regulator.

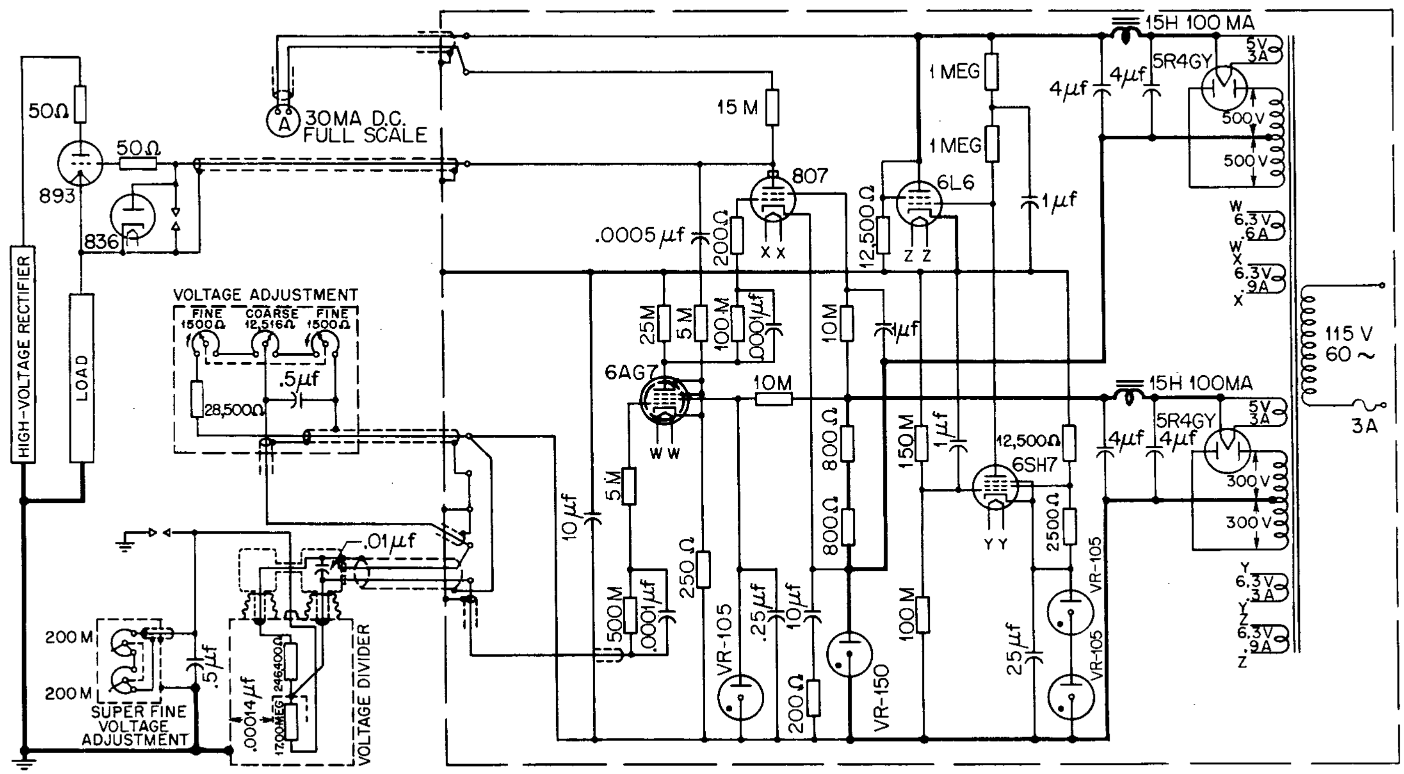


Fig. 7.7 — Schematic diagram of Beta decell voltage regulator 2.

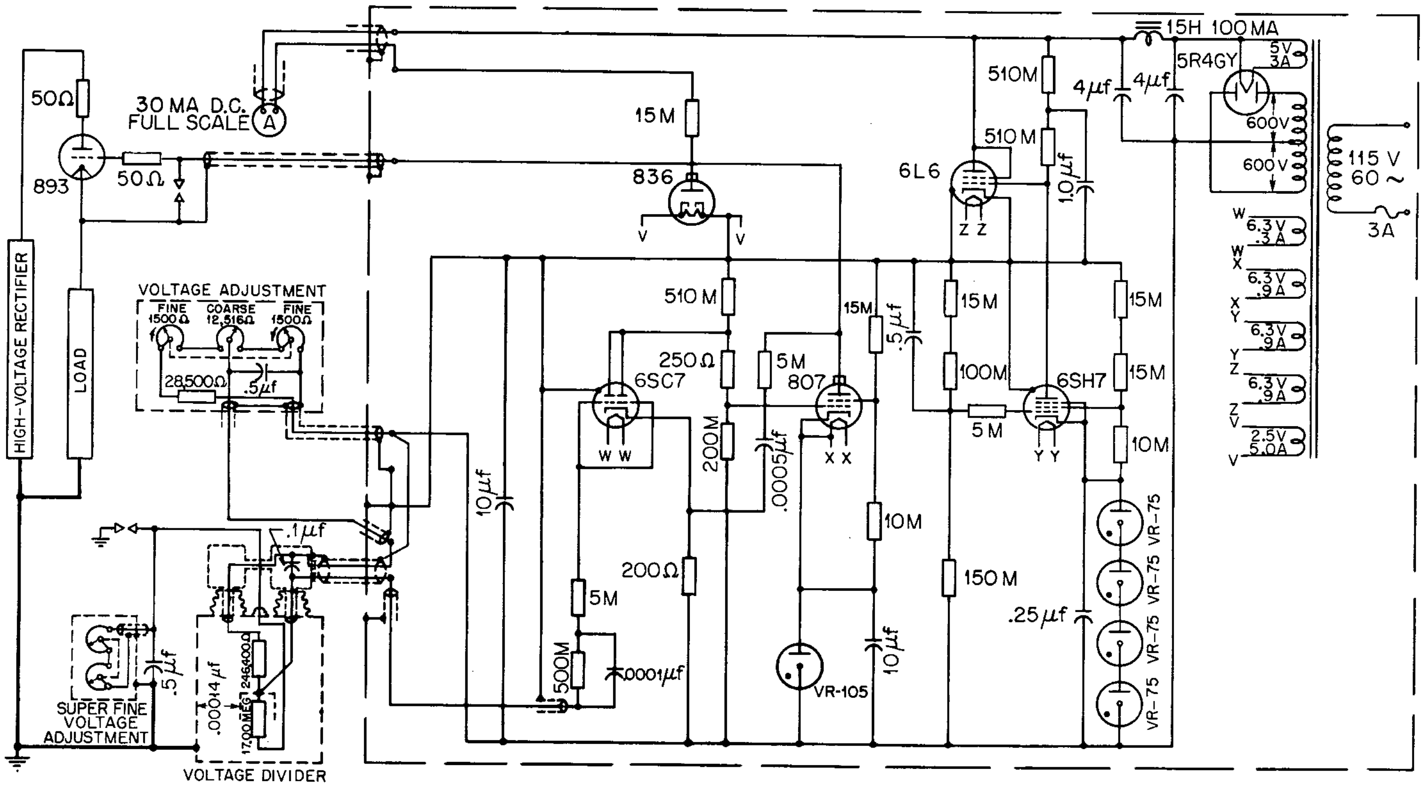


Fig. 7.8 —Schematic diagram of Beta decell voltage regulator 3.

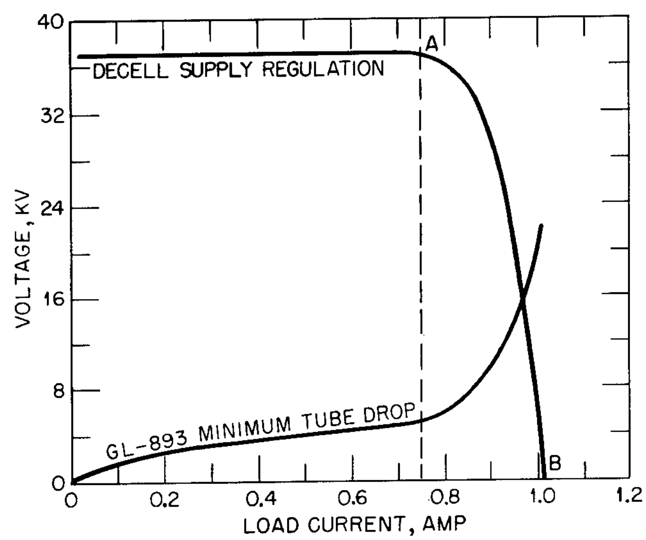


Fig. 7.9—General Electric GL-893 triode-tube emission-limit characteristics. Cutoff ratio is 1.45.

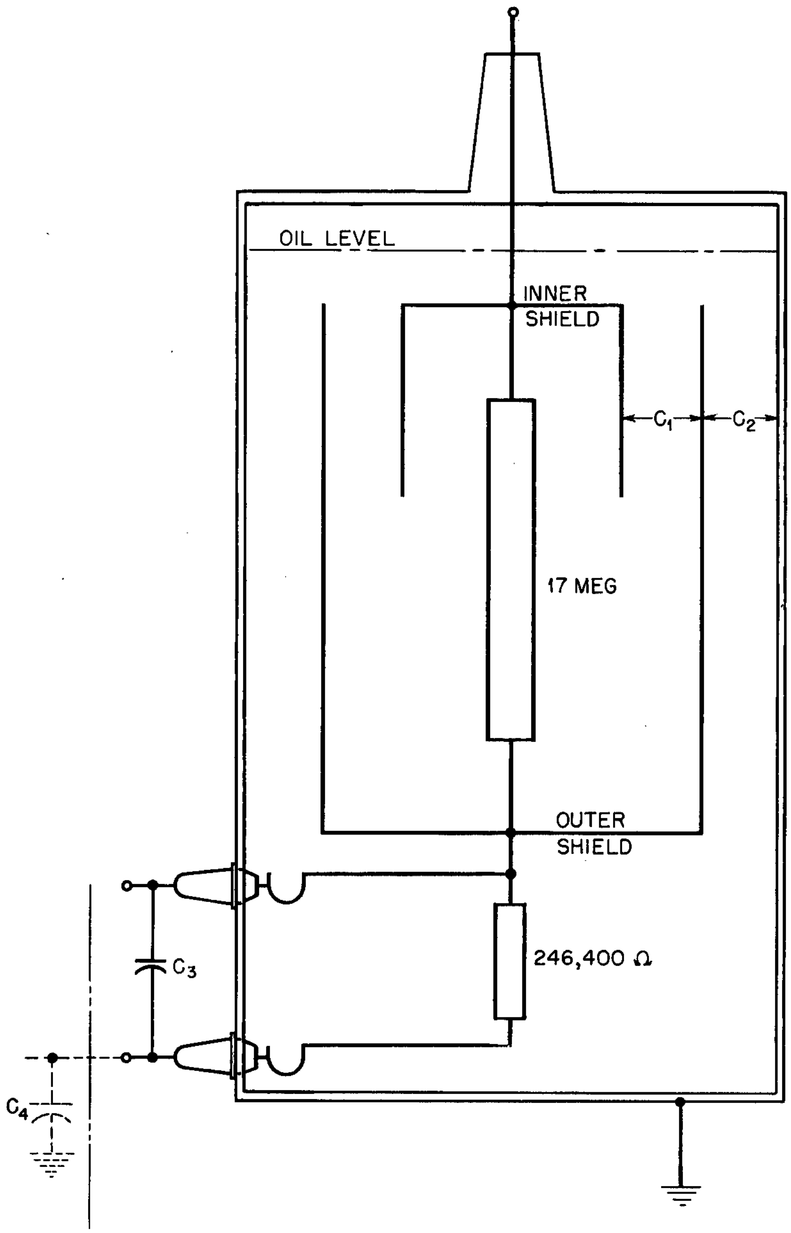


Fig. 7.10 —Schematic diagram of Alpha I voltage divider.

Fig. 7.11 —Alpha I voltage-divider coil assembly.

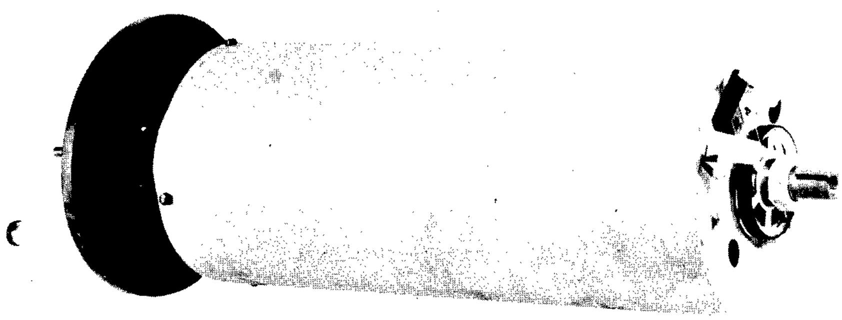


Fig. 7.12 —Alpha I voltage divider with outer tank removed.

Fig. 7.13 —Alpha I voltage divider.

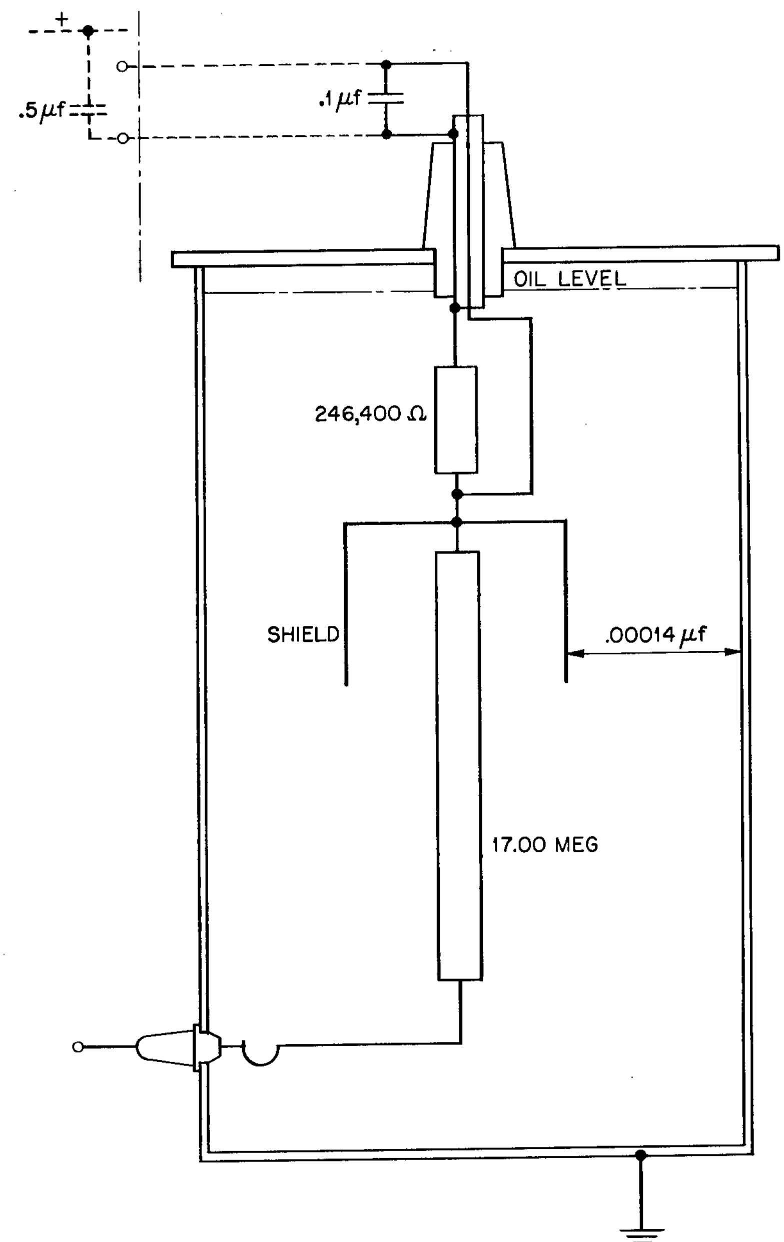


Fig. 7.14 —Schematic diagram of Alpha II and Beta (type 1) voltage divider.

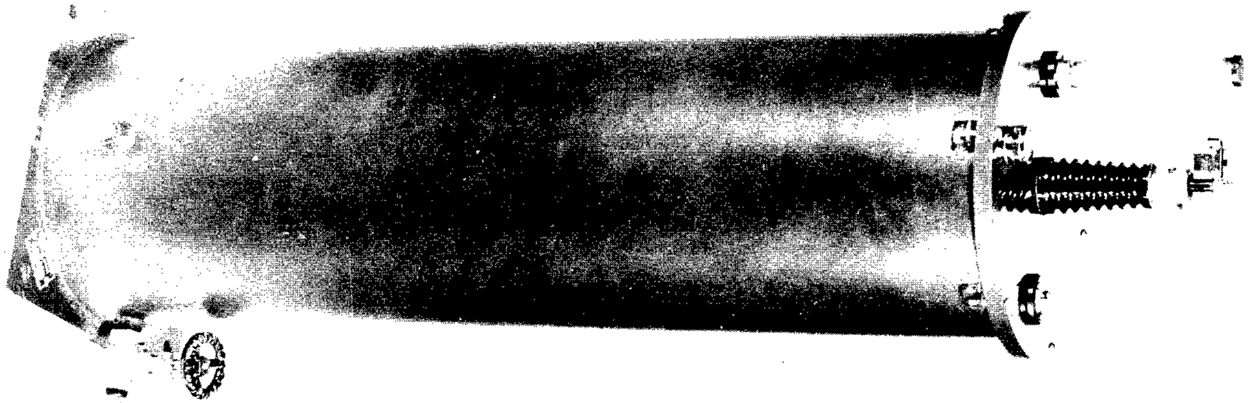


Fig. 7.15 — Alpha II and Beta (type 1) voltage divider with tank removed.

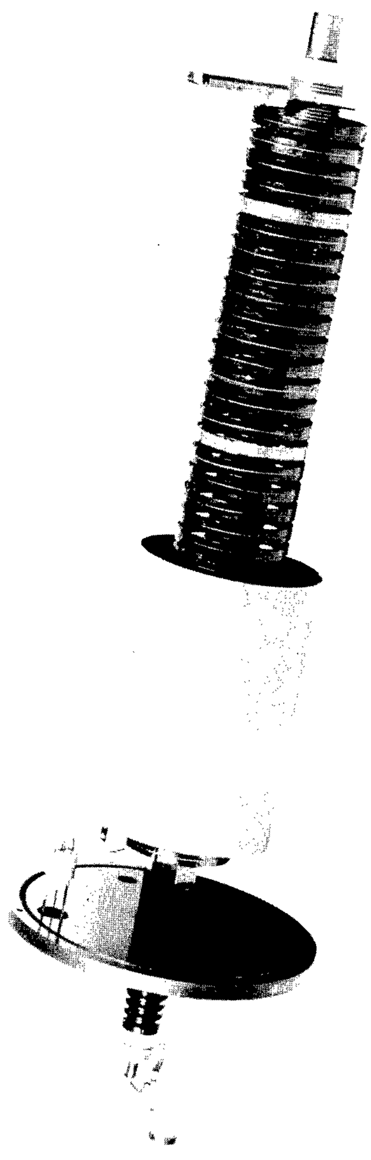


Fig. 7.16 — Alpha II and Beta (type 1) voltage divider.

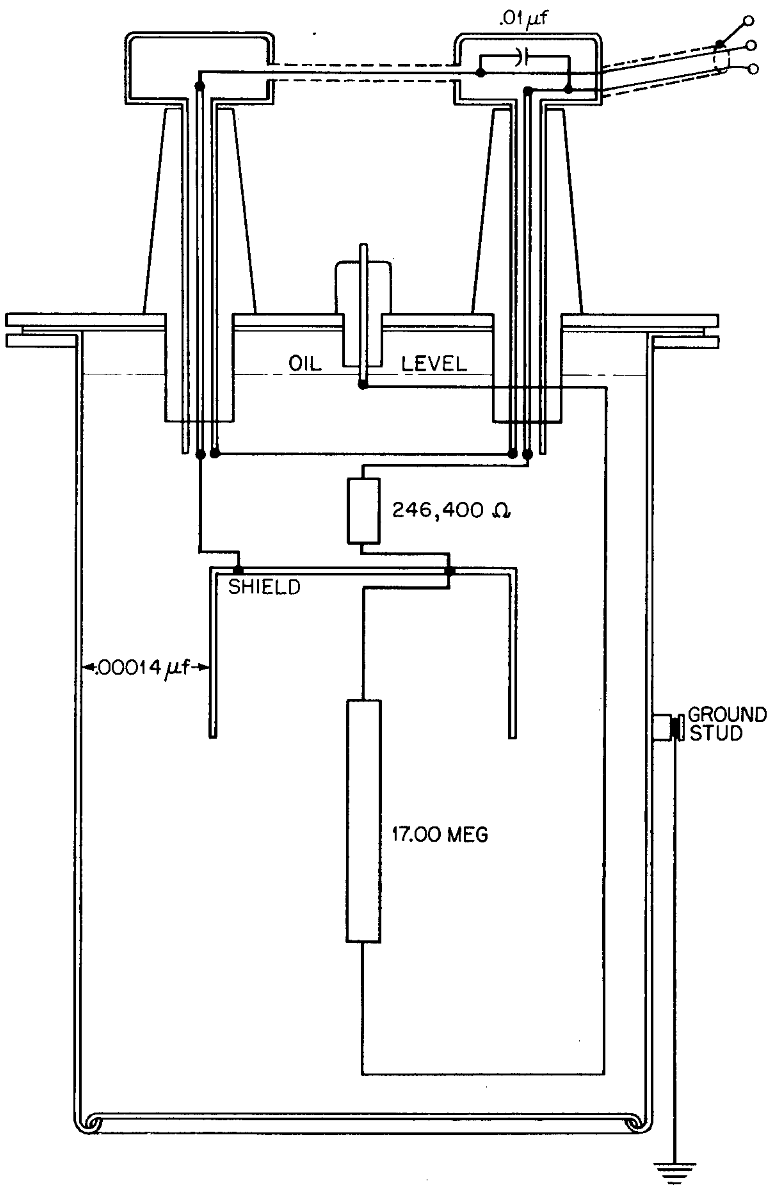


Fig. 7.17 —Schematic diagram of Beta voltage divider 2.

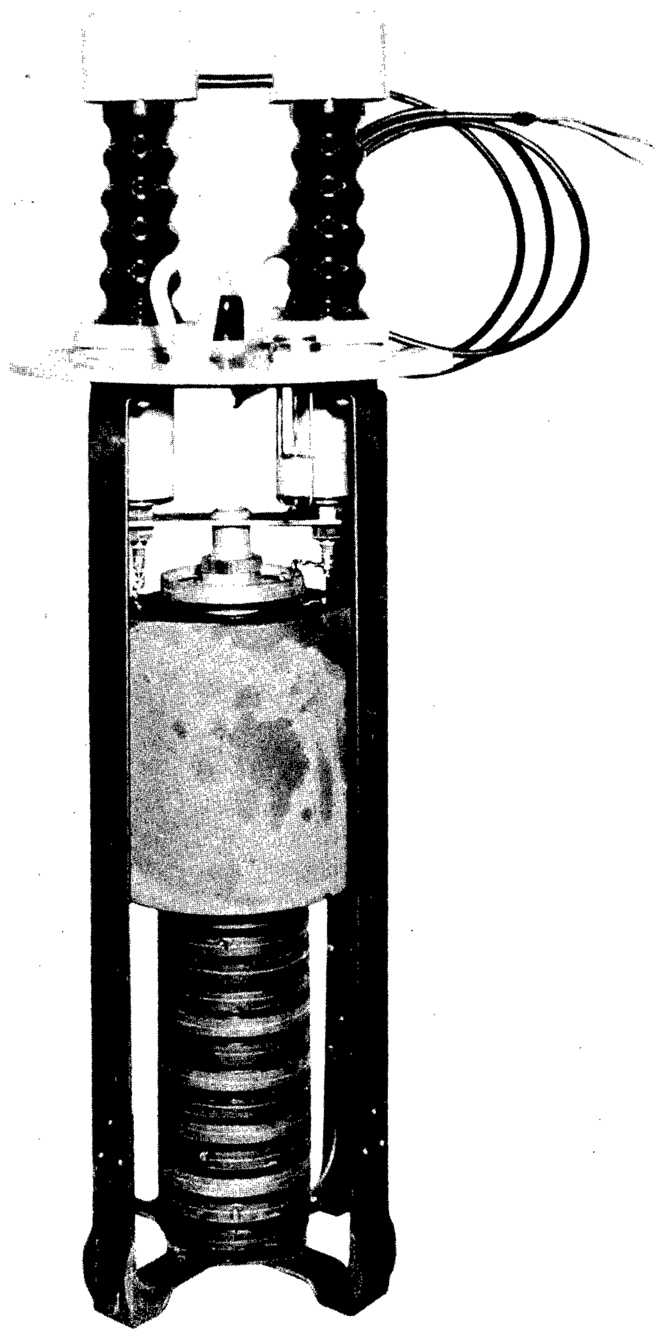


Fig. 7.18 — Beta voltage divider 2 with tank removed.

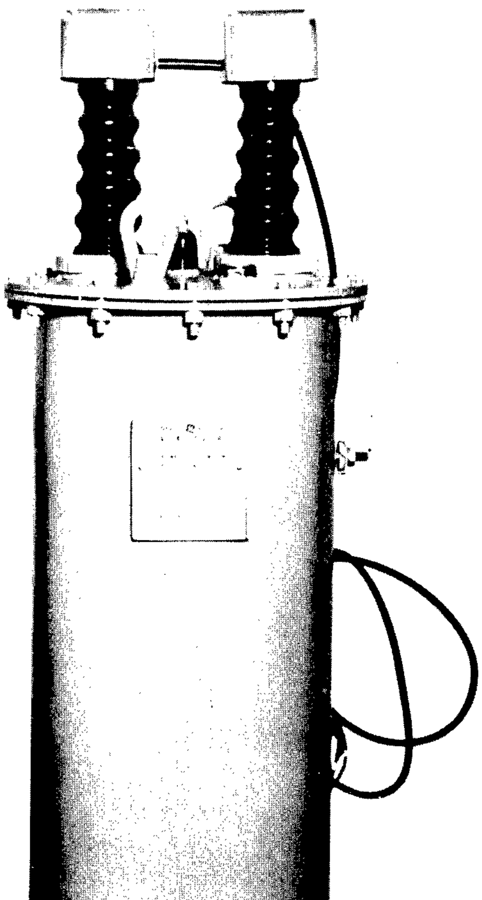


Fig. 7.19—Beta voltage divider 2.

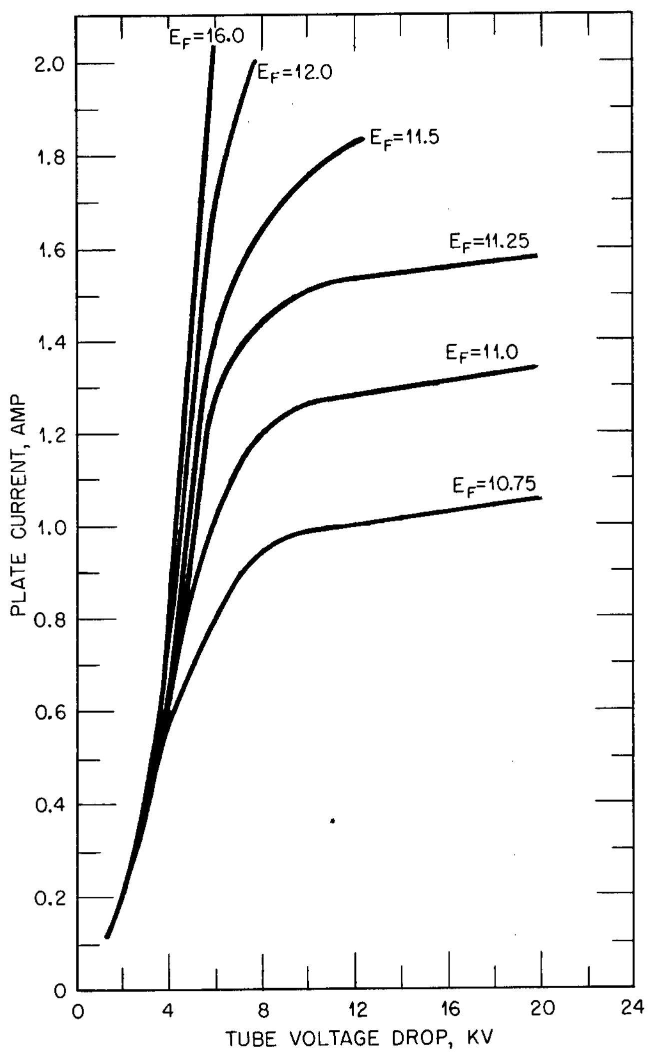


Fig. 7.20 — Characteristic curves of General Electric GL-893 water-cooled triode tube.

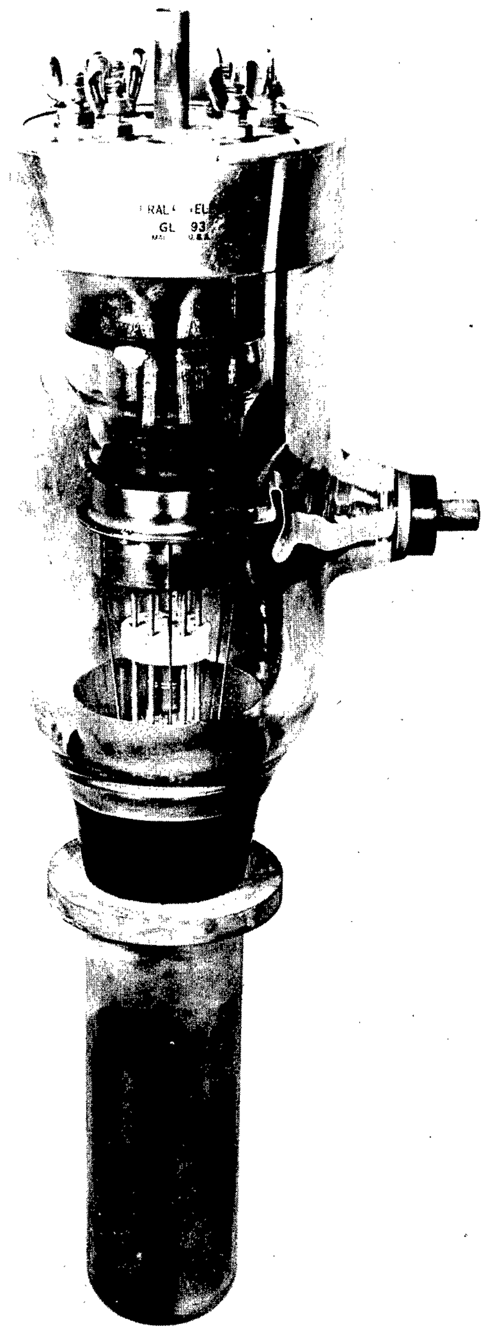


Fig. 7.21 —General Electric GL-893 water-cooled triode tube.

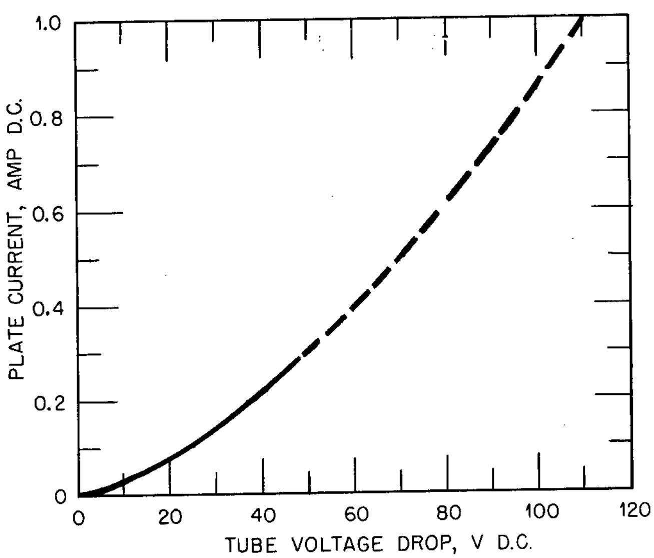


Fig. 7.22—Characteristic curve of 836 diode tube.

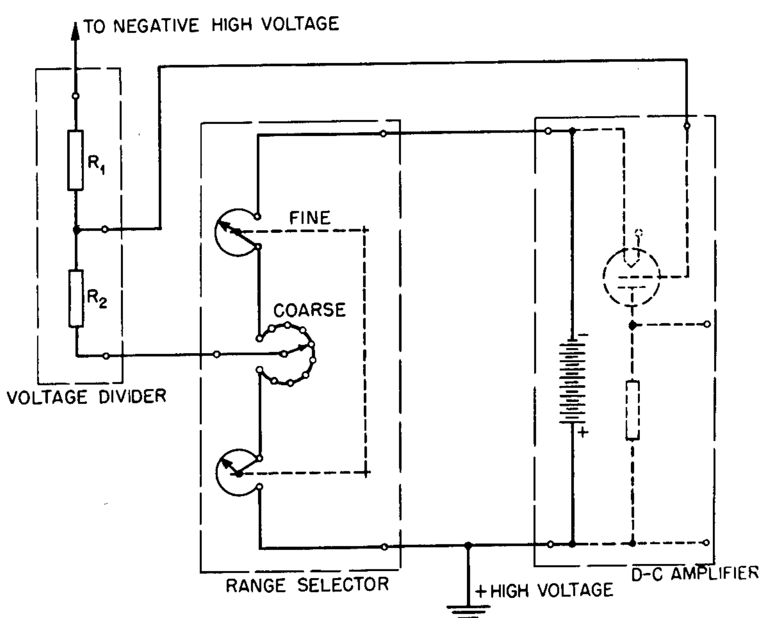


Fig. 7.23—Simplified diagram showing the relation between the voltage divider, range selector, and the standard voltage of the d-c amplifier.

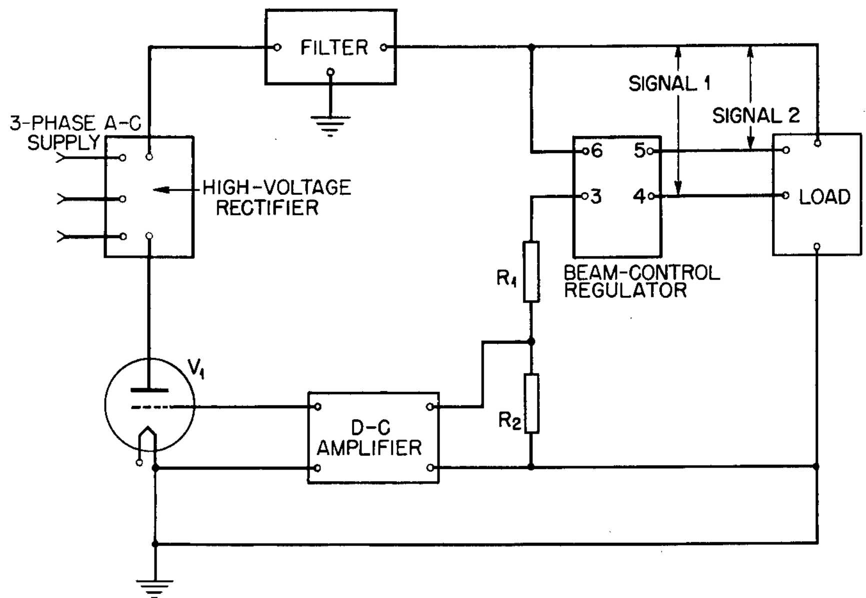


Fig. 7.24—Block diagram showing the relation of the beam-control regulator to the regulated high-voltage system.

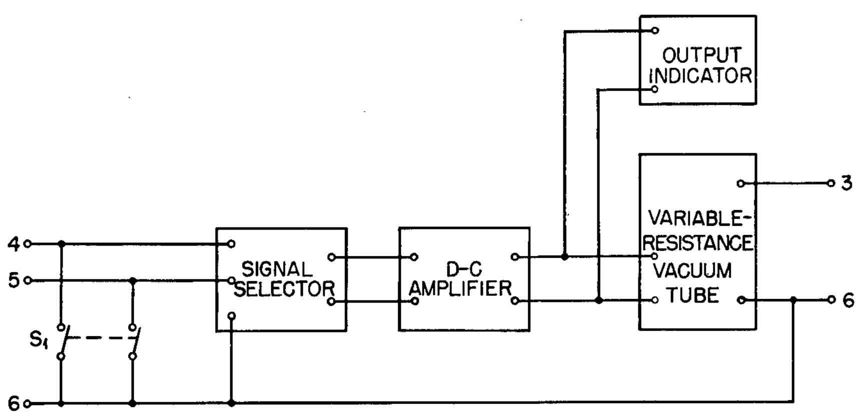


Fig. 7.25—Block diagram of the beam-control regulator.

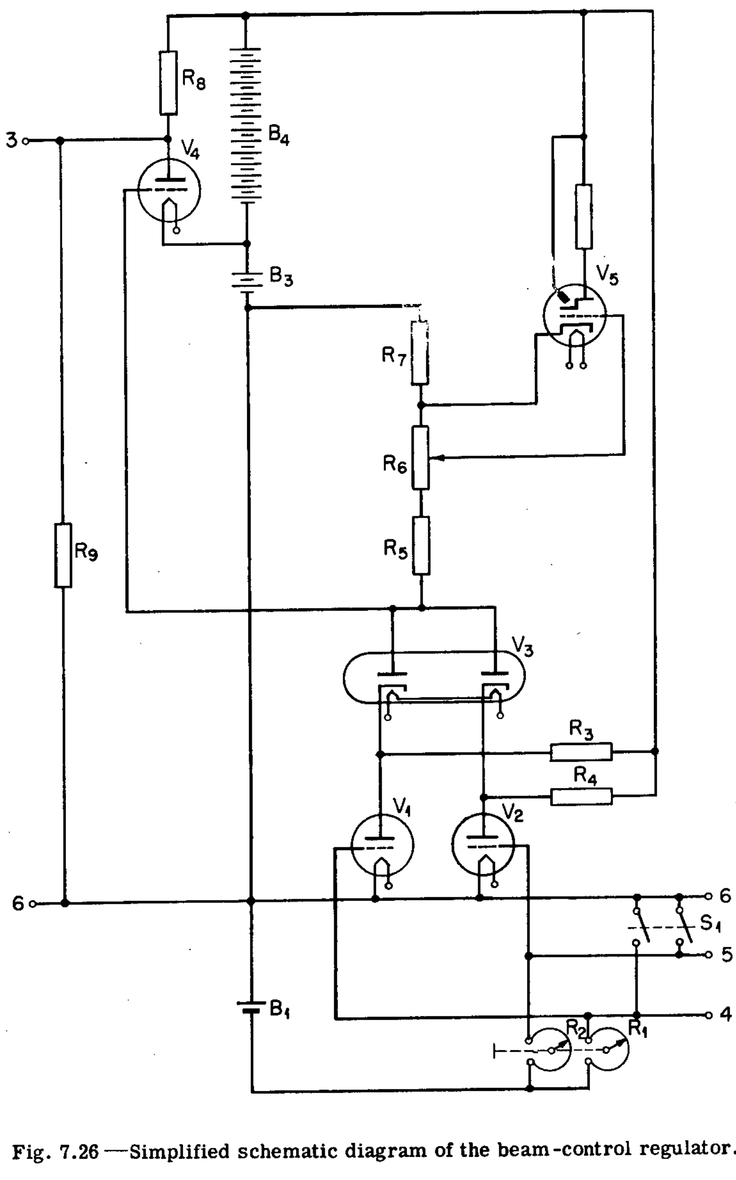


Fig. 7.26—Simplified schematic diagram of the beam-control regulator.

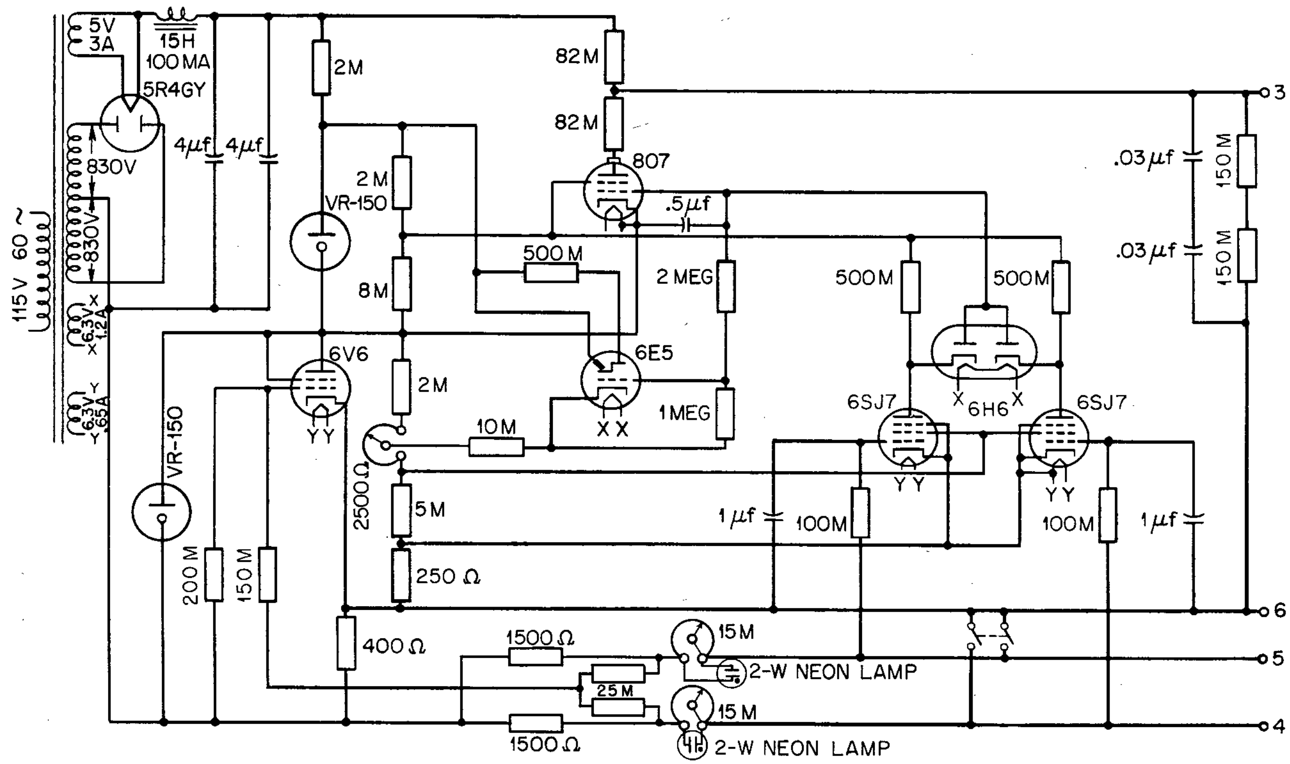


Fig. 7.27 —Schematic diagram of Alpha I beam-control regulator.

Chapter 8

CHANGES IN REGULATORS

Both the decell voltage regulator and the beam-control regulator, described in Chap. 7, required numerous changes during the period of plant operation.

1. CHANGES IN DECELL VOLTAGE REGULATORS

One of the first changes made consisted in strapping-out a 250-ohm section of the 6AG7 input-stage cathode resistor. This was done in order to decrease the degree of feedback in this stage and thus to increase the over-all gain of the d-c amplifier.

A change in operating procedure, undertaken in an attempt to increase production, necessitated the use of a higher decell voltage. In order to obtain this higher decell voltage from the main power supply, it became necessary to change the ratio of the voltage divider. This was done by shunting the low-resistance section of the divider with a 1.0-megohm resistor. As a consequence the voltage overshoot characteristic of the regulator system was impaired. In order to retain the desired transient characteristic for the divider it was necessary to maintain the time constants of the two sections at their former values. This required the placing of a new shunting capacitor on this divider. This change was made on all the cubicles operated at the plant, and oscillographic studies were made to obtain the optimum overshoot characteristic.

In the Beta equipment it was found that the normal fine control of the regulated decell voltage, as supplied with the original equipment, was still too coarse, owing to the mechanical construction of the receiver, to give the small adjustment necessary. To provide the necessary close control needed for the decell voltage, a vernier control was added. This consisted of two 200,000-ohm 11-watt General Radio potentiometers operated in tandem and connected in series between the high-resistance section of the main voltage divider and ground. This scheme provided a means of changing the ratio of the high-voltage di-

vider and provided the degree of control required. This potentiometer combination was located on the front door of the high-voltage cubicle within convenient reach of the cubicle operator.

It was found after the start of operation that the circuit constants associated with the GL-893 regulator tube were such that, under certain conditions of operation, parasitic oscillations were generated by this tube which were detrimental to the operation of the regulator system. To cure this condition 50-ohm resistors were installed in the grid circuit of the GL-893 in the Alpha I and Beta equipment, these resistors being mounted on the grid cap of the tube. Further oscillation suppression was accomplished in the Beta equipment by the addition of a 50-ohm resistor in the anode circuit mounted directly on the water jacket of the GL-893.

The physical location of certain of the capacitors used on the d-c amplifier chassis of the high-voltage regulator was such that these capacitors became overheated. It was therefore necessary to relocate such capacitors in relation to the power transformer, tubes, and various resistors in the chassis to prevent overheating and resultant failure. This change was made in the Alpha I regulator by CEW-TEC and by General Electric in regulators of subsequent design.

In the Alpha I regulator it was found that the input leads to the d-c amplifier received extraneous signals picked up from high-frequency radiation due to sparking at the load. It was therefore necessary to reroute these leads to reduce the stray pickup. This resulted in an improvement in regulation.

A separate tube was used in the Alpha I equipment for emission-limiting the regulated high voltage. Since the GL-893 regulator tube was not emission-limited, during tank sparking the runaway condition of its grid, caused by high positive voltage, did not occur, and therefore the use of an 836 tube from grid to filament was not necessary. To simplify maintenance and reduce operating cost the 836 tubes were removed from all the Alpha I cubicles.

Investigation of failures of various component parts of the regulator d-c amplifier disclosed that owing to its physical location in the high-voltage cubicle the components located under the chassis were operating at excessive temperature. Tests indicated that because of lack of ventilation in this portion of the cubicle the amplifier was operating at approximately 120°F. In order to provide additional ventilation and thus prevent overheating and failure of these components, the amplifier chassis was provided with a bracket to hold one side of the chassis away from its mounting plate. The hinges between the chassis and the mounting plate on the opposite side of this bracket were used to support the weight of the amplifier chassis.

In the original Alpha I equipment the location of the high-voltage divider in the high-voltage cubicle was such that the spark-plug terminals for the low-resistance section extended into the passageway running through the cubicle. It was found that the mechanics inadvertently broke the spark plug on this divider during their movement about the cubicle. Replacement of these spark plugs necessitated draining the oil from the voltage divider. This increased the danger of moisture absorption and subsequent breakdown of the divider resistances. In order to correct this frequent trouble the main voltage divider was rotated 90 deg, the spark-plug terminals thus being placed away from the open passageway.

A further source of trouble in the Alpha I and Beta cubicles was the water-flow switch used to protect the water-cooled regulator and limiter tube. The contacts of this switch were so located in the interlock circuit that a ground at a cubicle-door interlock would place the contacts of this switch directly across the control-power transformer. Such a condition would destroy the water-flow-switch contacts without blowing the control-power transformer protective fuse. This in turn would cause considerable outage time with the resultant loss in production. To correct this condition the contacts of the water-flow switch were placed in a different location in the control-power interlock sequence and were separately fused by means of a 1.0-amp fuse.

In the Beta equipment, owing to the smaller size of the tank unit, drain currents during sparking and unstable operation were limited to a maximum that would not damage the equipment. A bake-out procedure was adopted for operation at the time of initiating runs while the tank equipment was still outgassing, which required that the 893 regulator tube be emission-limited at a much lower value than during the normal run period. A bake-out switch was provided to run the filament induction voltage regulator down to a predetermined value established by a limit switch so adjusted as to give an emission-limit value of the order of 60 to 65 per cent of the emission-limit value during normal running. Since the emission-limit during bake-out was then below the protective relay settings, no protection was available for sustained concentrated drain currents. In order to overcome this, an auxiliary relay controlled by the bake-out switch was installed. This relay placed a resistor in parallel with the IAC current coil during the run period. The protective IAC relays were then calibrated with the shunt removed to give protection for the lower value of emission-limiting during bake-out. With the IAC relay coil shunted by the resistor, the resistor was adjusted to give a value of IAC tripping current that would offer protection for the higher value of emission-limiting used during the run period. The usual ratio of emission limit for bake-out to the emission limit for normal operation was 1.4 to 1.

2. CHANGES IN BEAM-CONTROL REGULATOR

The changes that were made by CEW-TEC are described in this section. The first of these changes was made in order to obtain a better means of measuring the regulator output since the 6E5 tube, V_5 in Fig. 7.26, had proved unsatisfactory for this purpose. The performance of these tubes varied so widely between regulators that a more positive indicating device was substituted in the beam regulators in the Alpha I plant. This indicator was d-c voltmeter calibrated for 750 volts full scale and placed across the output of the beam-control regulator (terminals 3 and 6 in Fig. 7.26). This device, however, was not entirely satisfactory since there was no way of knowing what the output voltage of the regulator would be when the voltmeter was switched into service. For this reason and because considerable mechanical trouble had been experienced with the regulator controls, it was decided that new regulators would be designed and purchased. These new regulators had a stand-by position on the control switch that did not disconnect the beam-control regulator from the main regulator circuit but provided a constant output voltage of known and readable value. This arrangement theoretically made it possible for the cubicle operators to adjust the high-voltage supply to the proper value before switching the beam-control regulator into operation.

Improper operation of a beam-control regulator could cause considerable contamination of the product, and it was soon found that even with these new regulators in the Alpha I plant this was occurring. Operating experience indicated that the same improper operation of the beam-control regulator was occurring in the Alpha II plant. Therefore a decision was made to remove the beam-control regulator from all operating equipment.

Chapter 9

ELECTRONIC REGULATORS: SERVICE RECORD, MAINTENANCE, AND STUDY

1. SERVICE RECORD OF ELECTRONIC REGULATORS

1.1 Decell-regulator Service Record. Although the actual decell operating voltage was approximately 39 kv whereas the voltage divider had been designed for 35 kv maximum, it was found that this increase in voltage did not cause overheating of the divider or breakdown of the insulation. Essentially no trouble was experienced with these dividers.

However, the coarse and fine control shafts of the regulator range selector were a constant source of trouble. The bearings used on these control shafts were inadequate and caused them to bind and become immovable. This necessitated removal of the range selector and substitution of a new unit. The defective unit was sent to the shop for the repair of individual bearings that were defective. It was also found that the cable used to connect the range selector to the decell voltage-regulator amplifier required numerous replacements because of faulty connectors.

In the Alpha I decell regulator the voltage standards, consisting of VR-150-30 glow-discharge tubes, gave a great deal of trouble. A study of the circuit constants of the voltage standards disclosed that these tubes were not operated at the most stable point on their current characteristics. Also, it was found that, although some tubes were reasonably stable at the normal operating current, others were extremely unstable. The tube characteristics were such that only a small number of tubes in any given lot had characteristic curves sufficiently free from sharp deviation to be usable. Therefore the trial of a relatively large number of tubes in each regulator was required to obtain a reasonably stable voltage standard.

Since the VR-105-30 glow-discharge tube had inherently higher stability than the VR-150-30, it was used as the standard in the Alpha II

decell voltage regulator. The use of these tubes reduced new-tube rejection, but the rejection rate was still extremely high.

General Electric Company also investigated the stability of various VR glow-discharge tubes and for the final design supplied Beta regulator 3, which utilized VR-75-30 tubes as a voltage standard. In this regulator the tubes were operated at 10 ma. This, however, was contrary to results of their own investigation, which showed that the most stable portion of the tubes' characteristic was at 5 ma. However, the over-all characteristics of the regulator for this design had the same over-all regulation as did previous regulators.

The major source of trouble in the d-c amplifier of the decell voltage regulator was found to be the input tube. The 6AG7 tube was used in all regulators, except in Beta regulator 3, which used a 6SC7. It was soon found that this was a particularly critical application for the 6AG7 tube, which had characteristics varying widely between tubes. Experience indicated that as few as 25 per cent of the tubes were usable for this application and that they could be selected only by trial operation in the d-c amplifier. In the case of the 6SC7 tube it was found that these tubes required frequent replacement owing to lack of emission.

In the d-c amplifier it was found that the power-supply filter choke failed owing to an insulation breakdown between the winding and ground. Although such failures occurred quite frequently, they were not of major importance when compared with the total number of regulators in service. However, in later models of the regulators these filter chokes were mounted on an insulating block. Power-transformer failures were also quite numerous, these failures being due to insulation breakdown between windings as well as between the windings and ground. Such transformer failures were particularly high in Beta regulator 3.

1.2 Water-cooled Triode Tube. An over-all picture of the triode regulator-tube development carried out during plant operation is presented in the form of a chart (Fig. 9.1), which indicates the various manufacturers who worked on such developments and the tube types developed by them.

(a) General Electric Tubes. The regulator tube initially installed was the General Electric GL-893. The characteristics of this tube were given in Chap. 7, Sec. 2. The average life of these tubes in regulator service was determined by choosing a representative sample and plotting the survival curve for this group (Fig. 9.2 and 9.3). It will be seen from these curves that the average life of this tube was not accurately determined since at the time of the Alpha plant shutdown a large percentage of these tubes were still in service. Referring to the survival curve for the regulator tube used in the Alpha I plant (Fig. 9.2),

it may be seen that at the end of the 11,000 hr of operation 43 per cent of these tubes were still in service. The survival curves for the GL-893 regulator tube used in Alpha II service (Fig. 9.3), indicate that for the second Alpha II track 73 per cent of the GL-893 tubes were still in operation at the end of 8,000 hr. The survival curve for the GL-893 tubes installed in the last Alpha II building indicates that 88 per cent of these tubes were still in operation at the end of 7,000 hr when the plant was shut down. Analysis of all tubes of this type that ultimately failed in actual production service shows the following:

Classification of tube defects	Per cent of group
Open filament circuit	13
Filament short circuit	2
Open filament lead	1
Grid-to-filament shorts, as shown by continuity meter	63
Damage to water-cooled anode	5
Accidental damage	1
Damaged element support	2
Broken or cracked envelope	1
Gassy tube, as determined by tests	8
Improper emission, as shown by tests	2
Miscellaneous	2

A total of 437 tubes are included in this analysis, being distributed by location of service as follows: Alpha I, 241; Alpha II, 150; and Beta, 46 tubes.

It will be noted from the above analysis that 63 per cent of all tube failures were caused by grid-to-filament shorts. The GL-893 tube had a 6-strand filament, with all these strands connected to a common header that, in turn, was supported by a central push rod. The spacing between this filament structure and the grid was 0.090 in. It was found in operation that unbalanced voltages on the strands caused unequal expansion of these strands, which in turn caused the filament structure to be distorted to the point where it would come into contact with the grid. In plant operation it was impossible to maintain the strand voltages balanced accurately enough to prevent such filament bowing, and thus grid-to-filament shorts resulted.

The grid of the GL-893 tube was wound on support rods, which extended to within ½ in. of the bottom of the anode. These supports were approximately 0.060 in. in diameter, and it was found that the voltage

gradient at the end of the grid-support rods tended to cause gas kicks in those regulator tubes which were operated emission-limited.

Owing to these obvious defects in the GL-893, General Electric redesigned this regulator tube, the new design being known as the "GL-623." In the GL-623 a corona shield cap was placed over the end of the six grid-support rods in order to prevent gas kicks caused by the voltage gradient at the end of these rods. The grid was constructed of tantalum so that it would absorb gas. The filament structure of this tube had been changed by replacing the six strands in the original design with three hairpin filaments. In the GL-623 tube these three hairpin filaments were supported by means of a common header, which, in turn, was supported by the central push rod. The legs of the hairpin filaments extended through holes in this header and therefore could, theoretically, expand individually without causing the entire filament to bow. In operation it was found that in many cases the clearance was not sufficient between the header and the filament strands and that these strands would tend to weld to the header. This condition often caused filament bowing and grid-to-filament shorts in the same manner as had occurred in the original GL-893. At the same time that this regulator tube was redesigned the test standards for this tube were increased. The maximum test voltage for GL-893 had been 30 kv, but the maximum test for the GL-623 was increased to 50 kv, 0.5 amp for 10 min and 60 kv, 0.9 amp for 1 min.

An analysis of 117 GL-623 tubes that failed shows the following:

Classification of tube defects	Per cent of group
Open filament circuit	7
Open filament lead	2
Grid-to-filament shorts, as shown by continuity meter	55
Damage to water-cooled anode	10
Damaged element support	1
Gassy tube, as determined by tests	18
Improper emission, as shown by tests	2
Miscellaneous	5

This analysis indicates that the improvement made in the GL-623 had only reduced the grid-to-filament shorts from 63 to 55 per cent, which was still too high to be acceptable. General Electric offered the development of a single-phase filament structure as the only possible way of eliminating such grid-to-filament shorts and, as a result, designed

and built such a tube, which was known as the "GL-679." Tests made using the GL-679 indicated that it would perform in regulator service as well as the GL-623 and that, because of its single-phase filament structure, grid-to-filament shorts would be less likely. However, since satisfactory 3-phase regulator tubes were being developed and since use of the GL-679 required changes in the filament-circuit components of the high-voltage cubicle, General Electric was advised that the development of a single-phase regulator should be discontinued.

Because of manufacturing difficulties at the General Electric tube plant, delivery of water-cooled regulator tubes was so slow that it became necessary to operate with only one regulator tube instead of two in parallel, as used in the original installation of the Alpha II high-voltage cubicles. As a result, 48 Alpha II high-voltage cubicles were operated with only one regulator tube per channel and with this tube set for 2.0 amp emission limit. Since the rectifier voltage was approximately 40 kv, this meant that during the time when the tube was operated emission-limited the anode dissipation reached a peak of 80 kw. However, it was found that in operation the failure rate did not materially increase owing to this single-tube operation.

(b) Westinghouse Tubes. To provide an additional supply of water-cooled triode tubes, Westinghouse was asked to submit a water-cooled triode that would be the mechanical and electrical equivalent of the General Electric GL-893.

To avoid the trouble experienced with the type of filament used in the GL-893, it was requested that Westinghouse tubes have a filament structure such that accidental single-phase operation of the filament would not cause grid-to-filament shorts. While such a tube was still being designed, the plant rectifier load current and load voltage gradually increased to the point where such an increase was limited by the minimum drop of the regulator tube. As a result the various tube manufacturers were requested to design a triode regulator tube that would have minimum drop and maximum cutoff characteristics. In order to obtain minimum anode voltage with zero grid voltage the specifications were changed to allow an amplification factor of 15 to 20 in place of the earlier amplification factor of 36. As a result of this request Westinghouse redesigned their regulator tube, the new design being known as the "WX-3245." This tube had the following characteristics:

Filament (3-phase, standard connection):	
Voltage (per strand), volts	10
Current (per strand), amp	61

Amplification factor	24
Maximum ratings, surge-limiting operation:	
Peak forward plate voltage, kv	60
Peak plate current, amp	10
Average plate dissipation, kw	20
Peak plate dissipation (3 min max), kw	85
Maximum negative grid voltage, volts	3,000

Samples of the WX-3245 were found to be extremely gassy and to have a filament structure that was inherently weak. Inspection of the sample tube disclosed that the filament-strand tensioning springs were so strong that the filament strands were easily broken when the tube was jarred, Also, it was evident that manufacturing technique was poor because a great deal of dirt could be seen on the internal surface of the anode. Since these defects could readily be corrected by Westinghouse for future tubes, samples of these tubes were tested in a Beta high-voltage cubicle, and the characteristic curves obtained are shown in Fig. 9.4. This tube was being redesigned by Westinghouse when the Alpha plant shut down, and the tube-development program was canceled.

(c) Machlett Tubes. E. Machlett & Son submitted a water-cooled triode tube known as the "ML-502," as the equivalent of the GL-893. The ML-502 tube had the following ratings:

Filament (3-phase, standard connection):	
Voltage (per strand), volts	10
Current (per strand), amp	61
Amplification factor	36
Maximum ratings, surge-limiting operation:	
Peak forward plate voltage, kv	60
Peak plate current, amp	4.0
Average plate dissipation, kw	20
Peak plate dissipation (for 2 sec), kw	60

In the ML-502, Machlett had used a filament structure that was radically different from that used in the GL-893. The filament structure of the ML-502 consisted of six catenary strands supported by means of a common header that, in turn, was supported by means of a central push rod. Machlett felt that this type of filament structure would prevent grid-to-filament shorts due to unbalanced strand voltages.

An analysis of a total of 37 ML-502 tubes that failed in service at the plant shows the following:

Classification of tube defects	Per cent of group
Open filament circuit	8
Grid-to-filament short, as shown by continuity meter	39
Damage to water-cooled anode	5
Accidental damage	5
Cracked or broken envelope	5
Gassy tube, as determined by tests	30
Miscellaneous	8

It will be noted from this analysis that the filament structure used in the Machlett ML-502 resulted in fewer failures from grid-to-filament shorts than had been experienced with either the GL-893 or the improved GL-623.

Machlett, along with the other manufacturers, was requested to design a regulator tube having a lower anode drop at zero grid bias. In order to obtain the lower anode drop it was necessary to decrease the amplification of this tube. The Machlett ML-501 tube, the result of this request for a new design, was submitted for test. One group of such tubes had an amplification factor of approximately 20, with an anode voltage drop of 4 kv at 1.0 amp, and a second group had an amplification factor of approximately 16, with a corresponding anode drop of 2.8 kv at 1.0 amp. This tube also differed from the ML-502 in that the filament structure had been changed, reducing the filament voltage per strand to 8 volts and the current per strand to 54 amp. Regulator tests made with the ML-501 in a standard cubicle indicated that tubes having an amplification factor of 20 were preferable, and the ML-501 was standardized with such an amplification factor. The same filament structure that was used in the ML-501 was also incorporated in the ML-502, and the resulting tube was known as the "ML-503." The ML-501 had the following ratings:

Filament (3-phase, standard connection):	
Voltage (per strand), volts	8
Current (per strand), amp	54
Amplification factor	20
Maximum ratings, surge-limiting operation:	
Peak forward plate voltage, kv	60
Peak plate current, amp	4
Average plate dissipation, kw	20
Peak plate dissipation (for 2 sec), kw	60
Maximum negative grid voltage, volts	5,000

The Machlett ML-503 had the following ratings:

Filament (3-phase, standard connection):	
Voltage (per strand), volts	8
Current (per strand), amp	54
Amplification factor	36
Maximum ratings, surge-limiting operation:	
Peak forward plate voltage, kv	60
Peak plate current, amp	4
Average plate dissipation, kw	20
Peak plate dissipation (for 2 sec), kw	60
Maximum negative grid voltage, volts	3,000

The ML-501 and ML-503 tubes were not developed in time to be used as standard replacement tubes prior to the plant shutdown.

(d) Federal Telephone & Radio Corp. Tubes. The Federal Telephone & Radio Corp. was also asked to become an alternate supplier of the GL-893 type water-cooled tube. The tube submitted by them was known as the "F-893" and was essentially the same as the GL-893. These tubes were installed for operation in the Alpha plants; and, of the 79 tubes installed, 21 had failed at the time the plants were shut down. An analysis of the failures of the F-893 tube showed the following:

Classification of tube defects	Per cent of group
Open filament circuit	5
Filament short circuit	5
Grid-to-filament short, as shown by continuity meter	66
Damage to water-cooled anode	19
Miscellaneous	5

It will be noted that the percentage of failures due to grid-to-filament shorts was essentially the same as that occurring with the GL-893 type, as would be expected since the filament structure was essentially the same.

When the first trouble was experienced with grid-to-filament shorts in the GL-893 and it was realized that such shorts were due to the type of filament construction used, which allowed bowing, Federal suggested the use of their F-124A filament structure. In the Federal type F-124A the filament structure consisted of 3 hairpins, the legs of these hairpins forming the six strands of the filament. The loops of these hair-

pins were supported by means of hooks fastened to a header and a central support rod in such a manner that the length of the individual hairpins could be varied independently. The Federal F-124A tube had ratings that were somewhat different from the GL-893 in that the F-124A had an amplification factor of 42, a filament voltage per strand of 13.6 volts, and a current per strand of 68.5 amp. Although this tube could not be used as a direct replacement for the GL-893 in the standard cubicle, a number of these tubes were obtained, and the filament circuit of certain cubicles was modified so that a test could be made of the filament structure employed by this tube. Operating experience with the F-124A indicated that this filament structure was superior to the other type since it could be operated with unbalanced filament voltages without resultant grid-to-filament shorts. As a result of these tests Federal was requested to redesign their F-893 so that a filament structure similar to that in the F-124A might be used.

After design work had been started on a modified F-893, changes in operation at the plant indicated that it would be desirable to have a regulator tube having a lower anode drop at zero grid bias, and Federal was requested to incorporate this feature in their new design. As a result of these two requests an experimental tube known as the Federal "D-4" was designed and tested. A regulation curve of this tube used in a Beta high-voltage cubicle is shown in Fig. 9.5. After this test the tube was redesigned and called the Federal "D-4C." The results obtained with this tube when it was tested in a Beta cubicle are shown in Fig. 9.6.

The results of these tests were so promising that it was decided to place this tube in production. Production models were known as "F-661." The ratings of the F-661 are given below.

Filament (3-phase, standard connection):	
Voltage (per strand), volts	10
Current (per terminal), amp	61
Amplification factor	29
Maximum ratings	
Regulator operation	
Peak forward plate voltage, kv	25
Average plate dissipation, kw	30
Peak plate dissipation, kw	50
Surge-limiting operation (emission-limiting)	
Peak forward plate voltage, kv	60
Peak plate current, amp	7.5
Average plate dissipation, kw	30

Peak plate dissipation, kw	60
Maximum negative grid voltage, volts	3,000
Surge-limiting operation (bias-limiting)	
Peak forward plate voltage, kv	60
Average plate dissipation, kw	30
Peak plate dissipation, kw	30
Maximum negative grid voltage, volts	3,000
Maximum duration of plate dissipation greater than 30 kw, sec	5

Unfortunately, at the time of the Alpha plant shutdown the inventory of regulator tubes at CEW-TEC was so large that none of the Federal F-661 tubes could be purchased and placed in plant operation; therefore no record of production experience with this tube is available.

1.3 Service Record of Beam-control Regulator. A major problem with the beam-control regulator was training the cubicle operator to become familiar with its operation and purpose. The use of an output indicator on the regulator did not help this condition. At one time it was thought that this indicator was the main reason why the operator did not understand the operation of the regulator, but after the indicator tube had been replaced by a meter, no improvement in operation was observed.

This situation gave rise to an investigation that indicated that the regulators were not so easy to operate as had been originally thought. As a result, 96 cubicles in Alpha I were equipped with a redesigned regulator, and additional operator training was given to determine whether the use of the new regulators would improve the quality of the product. Experience disclosed that, although better regulation was provided, the increase in production was insufficient to justify its cost.

The major objection to the beam-control regulator concerned a mechanical defect. Each of the two controls on these regulators was operated by means of a polystyrene rod that gave the necessary insulation between the beam-regulator chassis, which was at high voltage, and the operator's grounded control panel. The original coupling supplied with these insulating rods used two setscrews to hold the rod. It was found that the torque required to operate the on-off switch, which was the most frequently used control, was far too high for the rod coupling to transmit without causing the setscrews to loosen because the polystyrene, a plastic material, softened under the pressure of the setscrews. A fairly successful modification consisted of a brass hub fitted over each end of the polystyrene rod, these hubs being secured to the rod by cement and a pin that extended through the hub and the rod.

In the original beam-control regulators each input circuit was protected from transient voltages by a 2-watt neon glow lamp. It was found, however, that such transient voltages were too large at times even for these lamps and as a result caused breakdown in the lamp socket and in the variable resistors of the input circuit. Later designs of regulators used dry disk rectifiers for this protection, but failure due to transient voltages persisted. The output circuit of the regulator was also protected from transients by a capacitor. However, there were numerous failures of the output-meter multiplying resistor, and it was believed that these were due to failure of the protective capacitor under excess transient-voltage conditions.

It was also found that in the beam-control regulator a continual source of trouble was the tube complement used in this regulator. The 6SJ7 input tubes V_1 and V_2 had to be carefully selected to fit the circuit components in each regulator, and unbalance in this first amplifier stage would prevent the transfer of the regulator control from one input channel to the second input channel, as described in Chap. 7, Sec. 3. This balance was so critical that only a small portion of a particular lot of tubes could be used for this type of service.

Owing to these difficulties with the use of a beam-control regulator and owing to the outage time, loss of production, and the fact that the beam regulator did not give a materially better product, it was finally decided that all attempts to use such a regulator be abandoned.

2. MAINTENANCE EQUIPMENT AND PROCEDURE

Because of the specialized nature of the circuits used in the various regulators, no attempt was made to repair these regulators in the operating buildings. Upon removal because of a failure in an operating channel, all regulators were sent to a central regulator repair station. Here the regulators were repaired by trained personnel specializing in the repair of one type of regulator.

The decell voltage regulators were tested for gain and regulating ability before they were sent out to be used as replacements. The method used for testing the degree of regulation consisted essentially of operating the regulator in a circuit analogous to a high-voltage channel. The test voltages, however, were of the order of several hundred volts instead of kilovolts.

In order to check the type 836 tubes used in conjunction with the decell voltage regulators, tube test sets were constructed and supplied to the operating buildings using these tubes. These tube test sets were designed to compare the emission of the tube under test with the emission of a standard 836 tube under the same conditions of filament and plate voltage. These tube test sets also contained a neon bulb, which

was used to indicate plate-to-cathode shorts in the tube under test before the test plate voltage was applied. These test sets were used for routine maintenance checks in the production buildings.

3. EXPERIMENTAL AND THEORETICAL STUDIES

Throughout the plant considerable work was done in measuring and correcting the overshoot characteristics of the various decell voltage regulators. When a spark occurred in the mass spectrograph, the decell voltage momentarily fell to zero, and when this spark was extinguished, voltage returned to near its previous value by the automatic action of the decell voltage regulator. The term "overshoot" was used to indicate that the decell voltage momentarily returned to a value higher than that which had existed prior to the occurrence of the spark. A similar term, "undershoot," was used to mean that the decell voltage failed to return to its previous value.

In the operation of the mass spectrograph some overshoot was desirable in order to prevent the U 238 beam from sweeping slowly across the U 235 receiving electrodes after a spark had occurred since such a sweeping action would cause contamination of the U 235 electrode. Experience has shown that overshoot in the amount of 100 to 300 volts was desirable. Values much higher than 300 volts tended to start additional sparks, which, if they recurred in rapid succession, were called "sparking flurries."

Overshoot-voltage measurements were made on a number of channels in each operating track with a compensated voltage divider and an oscilloscope. As a result of such measurements the time constant of the low-resistance section of the main decell voltage divider was changed to adjust the overshoot characteristic to within the required 100- to 300-volt range. Using the overshoot measurements made on these channels, the correct value of capacitance was selected for use in the low-resistance section of the main voltage divider to give the proper overshoot characteristics.

It was found that, for particular voltage divider and channel, the d-c amplifier had essentially no effect on the overshoot characteristics of the decell supplies.

In general, the recovery characteristics of the decell supplies were so adjusted that this voltage reached a value of 100 to 300 volts above the nominal of 39 kv in approximately 26 msec; the voltage then returned to its nominal value in approximately 50 msec. Studies of the over-all regulation characteristics of the three systems were made. The results of these tests have been discussed, and regulation curves have been given (Chap. 6, Sec. 1).

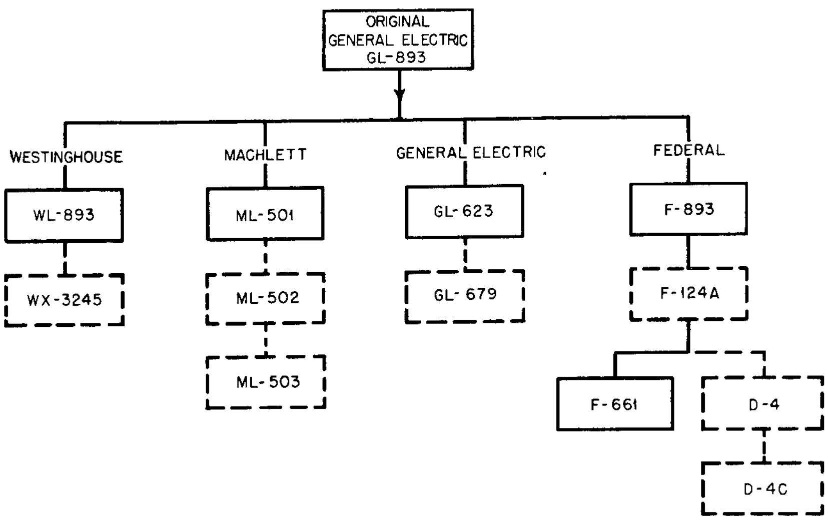


Fig. 9.1—Water-cooled triode regulator development. Solid lines, production tubes. Broken lines, experimental tubes.

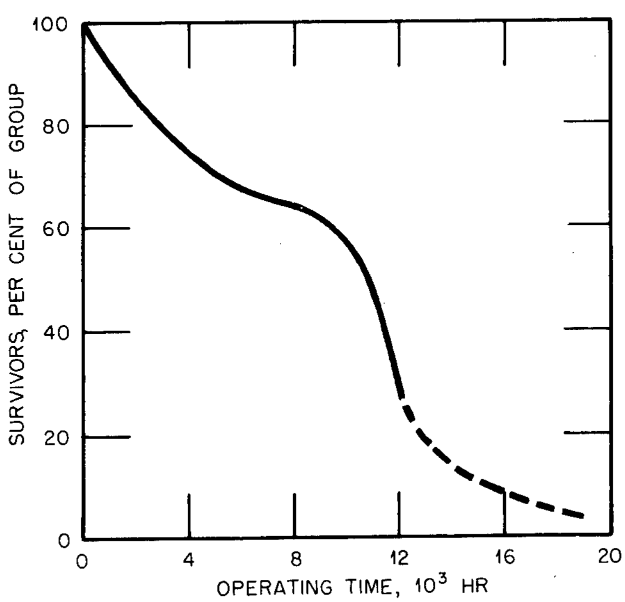


Fig. 9.2—General Electric GL-893 triode-tube survival curve for Alpha I decell regulator service. Dashed portion shows predicted future behavior.

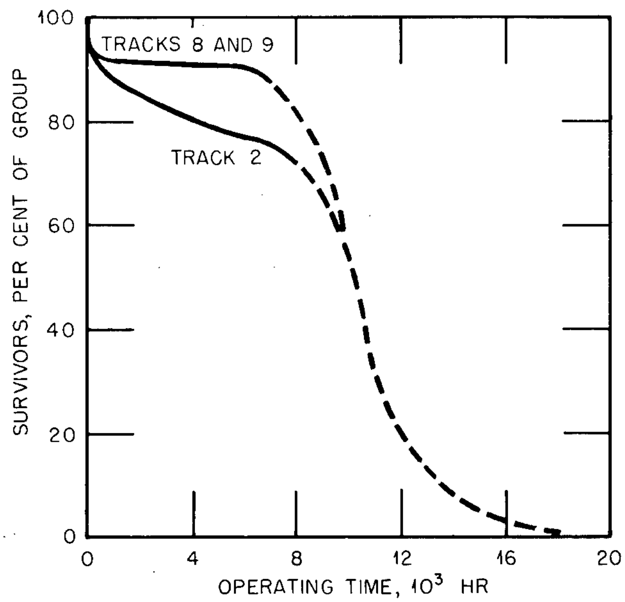


Fig. 9.3—General Electric GL-893 triode-tube survival curves for Alpha II decell regulator service. Dashed portion shows predicted future behavior.

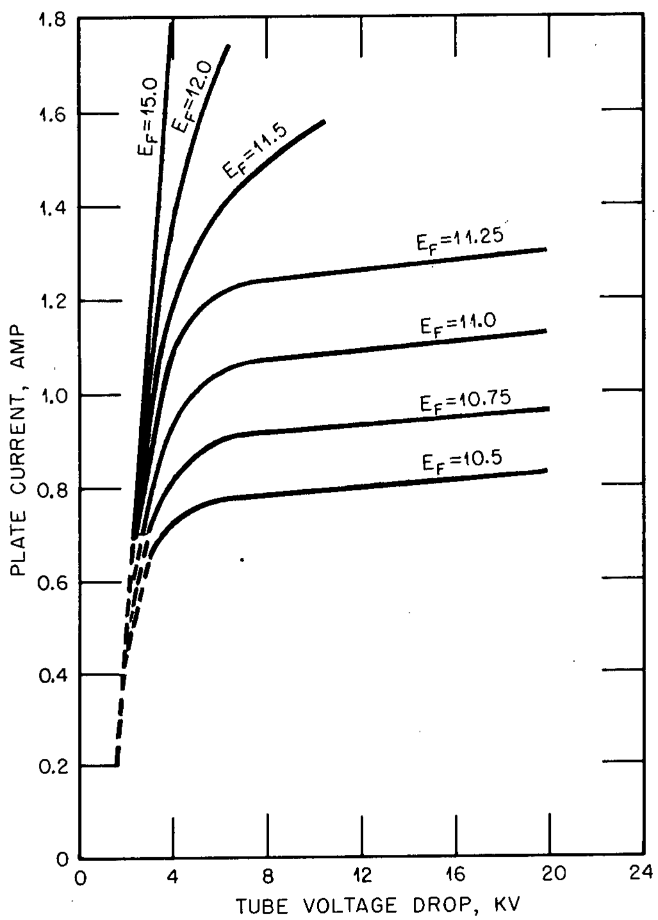


Fig. 9.4 —Westinghouse WX-3245 water-cooled triode-tube characteristic curves. Filament voltage measured line to line.

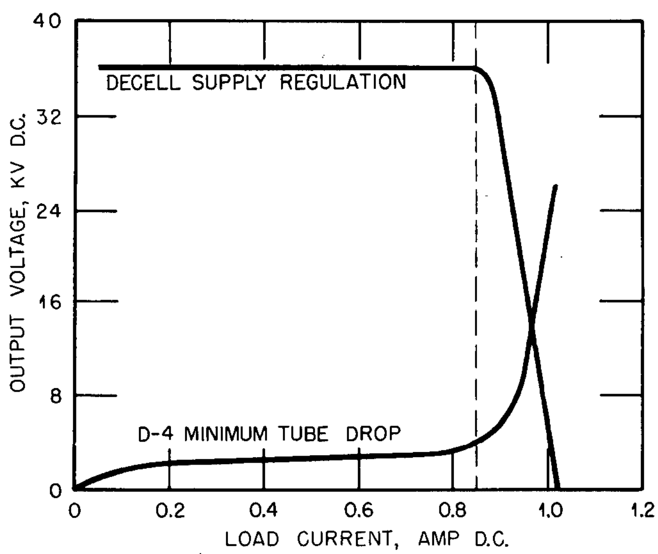


Fig. 9.5—Beta decell rectifier regulation curve using a Federal D-4 regulator tube having a cutoff ratio of 1.19.

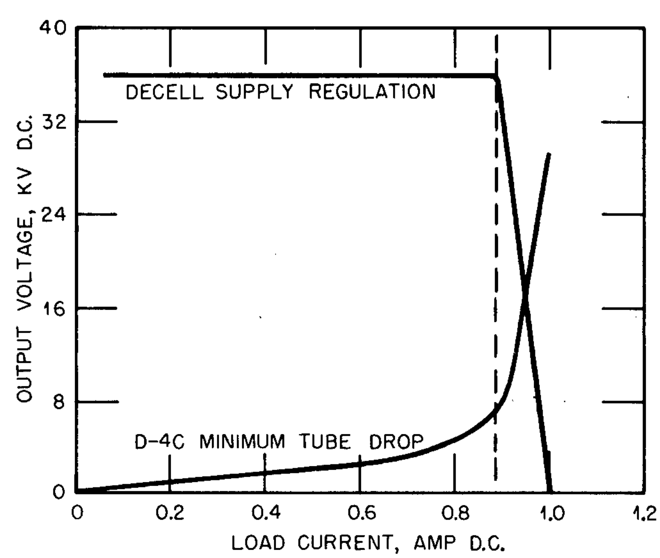


Fig. 9.6—Beta decell rectifier regulation curve using a Federal D-4C regulator tube having a cutoff ratio of 1.12.

Chapter 10

EQUIPMENT FOR PERSONNEL PROTECTION

The high-voltage equipment as received was either enclosed in metal cubicles or had barriers made of Transite and wood to keep personnel from coming into contact with energized high-voltage equipment. In addition to having these safety features the high-voltage cubicles were equipped with grounding switches, which operated in connection with the electrical interlock circuit to ground the high-voltage conductors and discharge the high-voltage capacitors when any of the entrances to the high-voltage enclosures were opened. These switches discharged the filter- and line-terminating capacitors in the high-voltage circuit and provided grounding to the high-voltage cables in the cubicles. Two such switches were supplied in each high-voltage cubicle, the first being connected in the accell rectifier and the second in the decell rectifier circuit. These switches were solenoid-operated, the solenoid being energized by the interlock control power circuit.

In the mass spectrograph all high-voltage connections were closed by means of wood, Transite, and metal barriers. Such enclosures were supplied with doors for easy access to the enclosed equipment for maintenance purposes, and the doors were interlocked with the high-voltage cubicle in such a manner as to deenergize the high-voltage supply when these doors were opened. To give further protection the doors were locked with a key, which during operation was placed in a solenoid-operated keeper. The key could not be removed from the keeper until the high-voltage-control power circuit was de-energized.

For the purpose of protecting personnel two electrical interlock sequences were utilized with the high-voltage equipment. The control power to the main power contactor was interlocked through safety switches that were placed on all doors entering the high-voltage cubicle. This first interlock sequence had a tank-operator permissive switch, which was in series with all other interlocks, and protection

interlock switches. When all these interlocks were properly set up and the manual switches under the control of the operator were in their operating positions, the main control circuit could be energized, closing the main power contactor at the cubicle.

At the time the main power contactor was energized, a second interlock sequence was initiated. The safety interlocks in this circuit consisted of interlock switches on the tank doors and barriers that enclosed and isolated the high-voltage connections at the mass spectrograph. These doors were also provided with a key-type interlock. When the doors were locked, the key was removed and inserted in a solenoid-operated key holder, which would hold the key in place when the high-voltage circuit was energized.

This key holder was also provided with an interlock switch that was connected in series with the door and barrier switches. The second interlock sequence was also provided with an emergency stop switch. Upon the proper setting up of all these safety interlock switches, the control power to the high-voltage cubicle could be energized by means of the manual-control power switch on the cubicle. At this time all personnel safety switches were closed, the high-voltage cubicle and the mass-spectrograph enclosure were both in safe operating condition, and operation could proceed at the discretion of the operator.

1. CHANGES MADE IN PROTECTIVE EQUIPMENT

The protective equipment described above was not considered by TEC as adequate for the safety of personnel. As a result certain changes were made in the equipment. These changes are discussed in this section.

Because of the uncertainty as to whether the grounding switches were operating properly and in order to ensure protection to the maintenance crew entering the high-voltage cubicle and the mass-spectrograph enclosure, grounding hooks were provided. These grounding hooks served to discharge capacitors and high-voltage supply lines and to indicate high-voltage equipment energized by the failure of interlocks or by frozen contactors. These hooks consisted of an insulated tube with a metal hook on one end. Attached to this hook was a woven-wire (Belden) braid ground shield. The other end of the braid was attached to a permanent ground. A rope was inserted through the woven-wire braid to prevent kinking of the braid and to prevent the possibility that the grounding hook would be left in position in an enclosure when the door to this enclosure had been closed. Such hooks were supplied at the entrances to all high-voltage enclosures.

It was found that the key interlocks originally furnished were not foolproof since it was possible that one key would fit more than one

lock. This key-interlock system operated on the principle that the enclosure doors could only be opened with a key and that this key could not be used unless the high-voltage circuits were deenergized. To eliminate the possibility that a key from another lock might be used, the keys were chained to their respective enclosures near the lock that they were to operate with lengths of chain that would not reach to adjacent locks.

The enclosure doors were constructed of wood and Transite. These doors were assembled with metallic hardware and were covered on the inside with a fine-mesh copper screen wire. Since this hardware had not been bonded to the screen wire and since the screen wire had not been grounded, these metal parts became charged to such a value that sparking resulted. Also, because mounting screws extended through the Transite doors, it was possible for operating personnel to come in contact with these charged metal parts and receive painful, if not fatal, shocks. This potential hazard was eliminated by bonding the metal parts of the door to the copper screen and then grounding this copper screen through a flexible ground strap to the grounded metal frame on which the doors were suspended.

The initial installation used MU-switches for door interlocks. It was found that, owing to misalignment of these doors, the overtravel limit of these switches could be exceeded and the switches broken. This type of switch was so constructed that when a failure of this type occurred the switch would be left in a closed position rather than in a normally open position, thus eliminating the protection expected from the switch. Although switches that had failed were replaced by switches of a heavier construction, it was still necessary to provide means for preventing such excessive overtravel.

In the Alpha I equipment a walkway had been placed above the high-voltage mass spectrograph. This walkway could be removed while the high-voltage equipment was in operation. When this walkway was removed, access could be gained to the high-voltage equipment while such equipment was energized. This presented a potential hazard, and it was felt desirable to interlock this walkway so that it could not be removed while the high-voltage circuits were energized. This resulted in the design of a mechanical interlock. Several experimental installations had been made at the time plant operation was discontinued. Material for a plant-wide installation of this mechanical interlock was on order at that time.

With the equipment as received, certain low-voltage auxiliary supplies appeared at the mass-spectrograph enclosure. These auxiliaries were not deenergized by the door interlocks. In order to eliminate this potential hazard the interlock sequence was changed so that all these auxiliary circuits would be deenergized when the enclosure doors were

opened. The sequence in the high-voltage cubicle was also changed so that the output of the decell regulator amplifier would be deenergized when the high-voltage cubicle doors were opened in the Alpha II equipment.

Owing to certain auxiliary circuits that needed to be kept energized for ease of maintenance, it was necessary to have the main 460-volt disconnect switch in the high-voltage cubicle closed at times when the cubicle was being entered by electrical maintenance personnel. As a precautionary measure against accidental energizing of the high-voltage circuit, insulating wooden blocks were furnished to be used to block open the 460-volt main power contactor. The location of this contactor was such that the wooden blocks could safely be inserted in the contactor before the cubicle was entered, thus eliminating the possibility of the contactor being accidentally closed.

The equipment as received had the holding coil of this main power contactor located in the ungrounded side of its interlocked sequence. This was hazardous since an accidental ground at any of the interlock switches would energize this coil. This condition was eliminated by moving the coil of the contactor to the grounded side of the interlock sequence, thus preventing accidental operation. In the Alpha II equipment further protection was added by the installation of a knife switch in the circuit that energized the main power contactor operating coil.

It was found that, in the high-voltage cubicle as installed, certain of the 460-volt terminals were exposed. These terminals were so located that it was possible for maintenance personnel to come into contact with the 460-volt circuit. As a result it was necessary to provide suitable insulating covers for the various exposed terminals.

2. PROTECTIVE-EQUIPMENT SERVICE RECORD

The service record of most of the personnel safety equipment shows numerous failures of all such equipment. In several instances the grounding switches had not operated properly or the capacitor-discharge resistors had burned out. This left the high-voltage equipment charged by the high-voltage capacitors. Such a condition was detected by the use of the grounding hook that was used when entering the high-voltage enclosure. It was found that the use of the grounding hook prevented many serious accidents. The defective switches found in plant operation were disassembled and reworked for proper alignment, after which there was a decided improvement in the operation of these switches.

The electrical interlock circuit and interlock switches were inspected at the end of each tank run. Numerous failures were found in these switches. A great portion of the failures resulted in failure of the switches to open when the enclosure doors were opened. This

condition was improved when the switches were replaced with microswitches and when proper means for limiting the degree of overtravel was provided. However, it was felt that a more suitable switch for this type of service would be one that had its movable contact fastened to the door and its stationary contacts fastened to the enclosure. In all probability this type of switch would have had more numerous failures because of misalignment of the door, but these failures would not have been dangerous and thus would have been tolerated. However, at the time of writing this type of switch had not been adopted for plant operation.

A second mechanical interlock scheme had to be provided because one of the tank doors was not supplied with an electrical interlock. This door was therefore mechanically interlocked with a second tank door, which could not be opened except by means of the key interlock, in such a manner that it could not be opened until the key interlock sequence had deenergized the high-voltage equipment.

Three fatalities at this plant due to electrical shock from high-voltage d-c equipment occurred. These were attributed to improper operation of safety equipment or violation of safety procedure. Several other accidents that occurred did not result in fatalities but were due to the failure of the protective equipment.

3. SAFETY PROCEDURE

Supplementing the safety devices described above for the protection of personnel, a rigid safety procedure was placed in effect for plant operation. This procedure provided for the routine inspection of all safety devices at the end of each run and outlined in detail the proper use of the grounding hooks that were provided at the entrance of each high-voltage enclosure.

The procedure for the use of grounding hooks required that upon the opening of a door to any of the high-voltage enclosures the grounding hook should be touched to a sufficient number of points within the enclosure to ensure the discharge of all capacitors and to make certain that the high-voltage circuit was not accidentally energized.

After such points had been touched to discharge the capacitors, the hooks were hung on both the accell and decell supply lines and left in that position as long as the door to the enclosure was open. It was felt that this procedure, properly followed, would prevent any accident even though simultaneous failure of all the safety devices should occur. In addition, when work was being performed in the high-voltage cubicle, the main contactor was mechanically blocked open as described in a previous section. It was only through rigid enforcement of the detailed safety procedure that many serious and fatal accidents were avoided.

Part II

AUXILIARY ELECTRICAL EQUIPMENT

INTRODUCTION TO PART II

Auxiliary electrical equipment, in addition to the high-voltage accelerating and decelerating equipment, was provided in the mass spectrograph to initiate and control its operation. This equipment consisted principally of supply and control circuits for the material to be vaporized, supply and control circuits for the ionization process, and monitoring circuits to indicate the quality and quantity of the product received.

1. Electric heaters associated with the sublimation chamber induced vaporization of a charge material (usually UCl_4) placed in the chamber and assured a flow of vapor adequate to maintain an electric arc in the ionization chamber.

2. Electric heaters associated with the ionization chamber and external members in the ion-accelerating region maintained temperatures in these regions above the temperature of the sublimation chamber to prevent condensation of the vapor.

3. Temperature-control equipment included in the circuits of the heaters regulated the flow of vapor and was an important factor in the efficiency of the ionization process.

4. Electrically operated and controlled valves were provided in some of the mass spectrographs for added regulation of the flow of vapor.

5. An electron source, usually a filament, provided electrons for ionizing vapor in the ionization chamber. Circuits for the source included a supply for heating the filament and an arc supply biasing the filament and ionization chamber to maintain an ionizing electric arc in the vapor.

6. Monitoring equipment associated with the ion receiver indicated the rate of reception of ions and, to some extent, the quality of the ionic product.

Development programs initiated many experimental variations in the individual components but, in general, did not alter the over-all functions of the auxiliary equipment.

Chapter 11

FILAMENT-SUPPLY EQUIPMENT

The filament was the electron source providing electrons for ionization of vaporized charges under conditions of adequate vapor pressure. The ionization process resulted in a dense arc of substantial current. The filament was usually a low-resistance tantalum wire heated to incandescence by a high current. It was placed at the proper position with respect to the arc chamber so that the magnetic field would collimate the electrons given off and establish the arc adjacent to the accelerating-electrode system.

1. FILAMENT SUPPLIES

Alpha I and Beta used a d-c supply for the mass-spectrograph filament, and Alpha II used an a-c supply.

The supplies for an Alpha I channel consisted of two multiphase dry-disk rectifiers, including transformers and copper oxide rectifier stacks mounted in a square metal enclosure approximately 2 by 2 by 2 ft. Forced-air cooling was supplied by a combination of the building-supply fan and an individual fan mounted in each rectifier enclosure. Each rectifier had a continuous rating of 300 amp at 6 volts direct current, supplied from a 460-volt bus through fuses, contactor, and saturable reactor (Fig. 11.1).

The two Beta multiphase dry-disk rectifiers were enclosed in a metal-clad cylinder and insulated from the cylinder. Each was rated 300 amp at 6 volts direct current (Fig. 11.2). The bus was energized from the cubicle-supply breaker through a fused disconnect switch. The rectifiers were energized from a 460-volt bus through fuses, a contactor, and a saturable reactor. The two rectifier insulating transformers were mounted in one oil-filled case provided with high-voltage bushings extending through its upper side, which contained the leads to the copper oxide rectifiers.

The copper oxide rectifier stacks were mounted on the top of these high-voltage bushings. The rectifier stacks had at the top of the case a blower that drew air through the bottom of the enclosure and across the stack and exhausted it through a sheet-metal hood. The supply for the rectifier was interlocked with the blower, ensuring cooling air before the rectifier could be energized. Access to the rectifier connections was gained through a door in the rectifier enclosure. The door was interlocked with the high-voltage control-power circuit, ensuring that this circuit could not be energized until the door had been closed. The output from the rectifier was fed through high-voltage cables extending through the top of the case. These cables consisted of two concentric conductors for filament supply with a third concentric layer as a common conductor for the arc and decell supplies. The filament-supply conductors were 500 M cir mils for the original installation. The size of these conductors was later changed to 800 M cir mils.

The Alpha I filament rectifier transformer was supplied with power from a 460-volt 3-phase bus through a saturable reactor rated 60 cycles, 3 kva, 3 phase, 265 volts alternating current, 125 volts direct current (50 and 75 per cent taps). This transformer was connected Y-delta, and the copper oxide rectifiers were connected delta to the secondary to form a 3-phase full-wave bridge-connected rectifier. The rectifier transformer had a step-down ratio of 400/6 volts. The Beta rectifier transformer had the same ratings as the Alpha I transformer and was fed in the same manner from a 460-volt bus through a saturable reactor. The Beta rectifier transformer was insulated for 58 kv direct current.

An a-c filament supply was provided for Alpha II and was controlled by a thyratron regulator instead of a saturable reactor (Fig. 11.3). The Alpha II supply was a step-down transformer rated 60 cycles, 2.7 kva, and 400/6 volts, insulated for 35 kv direct current, and energized from the cubicle 460-volt main power contactor through fuses and a regulator panel. Two such transformers were mounted in a single oil-filled case, and the secondary windings were connected to the mass-spectrograph filament by high-voltage cables through potheads in the top of this transformer case.

The filament supplies were protected by 10-amp fuses placed in the 460-volt supply lines. Additional protection for the Alpha I and Beta rectifiers was provided by interlocking the cooling fans with the rectifier supplies.

Metering for the filament supply in Alpha I, Alpha II, and Beta was supplied by a 0.10-amp a-c meter provided in one phase of the primary to the rectifier transformer. Since this was the only meter in the filament circuit, all regulation of the filament current in the plant was

accomplished by using the current in the primary as the reference. The actual filament current could be obtained by the use of a calibration factor.

2. OPERATIONAL HISTORY OF THE FILAMENT SUPPLY

In the operation of the mass spectrograph prior to the time that an arc had been established in the ion source, the filament was operated at a predetermined maximum temperature, but as soon as an arc was established, the filament temperature was reduced and controlled by means of the filament-arc regulator. During this initial start-up, the Alpha I filament rectifier supply was operated at approximately 107 per cent of its rating for a period of about 4 hr, and the Beta equipment was operated at approximately 110 per cent of normal load for a period of about 1 hr. The Alpha II ion-source filament was operated on alternating current from a transformer instead of from a rectifier. This filament-supply transformer was rated 2.7 kva, 400/6 volts but was operated at only 0.89 kva under normal operating conditions.

The Beta filament rectifier required the use of an air-flow interlock switch in the forced-air cooling system. The original switch was a crude device using machine screws as contacts. These contacts were closed by the pressure of the cooling air on a vane attached to a lever operating the switch. Owing to the construction of this switch and the type of contacts used, the action was not positive, and the switch caused much trouble. The construction of the rectifier enclosure and the location of this switch made it necessary to disassemble the enclosure in order to service the air-flow switch. The switch was rebuilt and installed in a position external to the rectifier enclosure.

The filament was subjected to a mechanical force, the direction of which depended on the direction of the current flow through the filament and the direction of the magnetic field. In ion sources that used a d-c filament supply it was found that the life of the filament was materially reduced for one direction of current flow. At the start of Alpha I operation such a reduction existed in 24 channels owing to reversal of wiring connections at the time of installation. This condition was corrected by reversing the polarity of the filament leads at the rectifier of these 24 channels.

Only two types of trouble were experienced with the filament-supply transformers, i.e., defective high-voltage pothead insulation in Alpha II and the infiltration of foreign matter through the bushings of the Beta transformers.

The high-voltage bushings of the Beta filament-supply transformers were not sealed, and owing to the forced-air cooling used on these rectifiers, dust tended to filter through the high-voltage bushings. The

presence of dust was likely to result in oil contamination. This could have resulted in serious trouble if it had not been corrected by sealing the bushings with a plastic compound.

The trouble experienced with the potheads in the Alpha II filament transformers was due to poor design and improper installation of these potheads. The failure rate for these potheads was high, but owing to lack of time and the expense involved no changes were made.

When the Alpha I and Beta filament-supply rectifiers were first placed in operation, a large number of faulty copper oxide disks were found. After these faulty disks had been replaced, normal service was experienced, with only a small percentage of failure.

One of the greatest sources of trouble in the Beta filament supply was caused by water entering the rectifier enclosure, causing arc-overs and a subsequent breakdown of high-voltage insulation. Condensation on cold-water pipes located directly above these rectifiers and overflow from water connections to the process equipment made it impossible to prevent an accumulation of water. It was necessary to provide an effective water seal at the rectifier enclosure. This was accomplished by the generous use of sealing compound around the high-voltage cables at the point where they entered the top of the rectifier enclosure. The outer braid of these high-voltage cables was saturated with glyptal to prevent capillary movement of the water through the braid. After these precautions were taken there was little more trouble.

In Alpha II, trouble was experienced with the protective fuses in the primary of the filament-supply transformers. Loss in production time resulted because a failure of the ion-source filament could not be distinguished from a failure of a protective fuse. A check had to be made by electrical-service personnel to determine the actual circuit fault. Since these fuses were in a position where they could not be easily checked, it was proposed that indicating lights be placed across the fuses in order that the source of trouble could be readily determined by the process operator. However, those lights had not been installed at the time of the Alpha II plant shutdown. Excluding the items already mentioned, the operation of the filament-supply equipment was normal for this type of equipment and application.

3. EXPERIMENTAL A-C FILAMENT SUPPLY

In Alpha I and Beta, experiments using four ion sources were initiated in an attempt to increase production. It was thought advisable to use a-c filament supplies in these tests rather than the d-c type used previously. An a-c supply had been used successfully in Alpha II, but

this test was made to determine whether such a supply could be used successfully in the Beta process, which used a stronger magnetic field. For the Beta experiment the filament rectifier was replaced with a filament transformer similar to the one used in Alpha II. The 3-phase saturable reactor was converted into a single-phase reactor, and the control circuit was rewired for the operation of the a-c supply.

In Alpha I the filament rectifier was replaced by a suitable transformer. The two ion-source filaments were connected in such a manner that the operating temperature of each could be adjusted independently. From an electrical standpoint the a-c filament proved satisfactory. In the Beta equipment, trouble was experienced with the filament because of the high current density in these filaments and because they were operating in a higher magnetic field than in Alpha II. Both experiments were abandoned.

4. INCREASED FILAMENT CURRENT

In an experiment in Beta and Alpha II the ion-source filament was redesigned to use a wire of larger diameter. Because this redesigned filament required an operating current of approximately 475 amp during the initial start-up, tests were made to determine whether the filament supplies could safely be overloaded to this extent. These tests disclosed that the filament-supply transformers in Alpha II and Beta could withstand this overload without serious damage. The Beta copper oxide rectifiers had sufficient forced-air cooling to allow them to operate safely at this current. In Alpha II and Beta the filament-connector cables used at the mass spectrograph overheated. The high-voltage cable used in the Beta equipment to connect the filament rectifier to the terminal box at the mass spectrograph was seriously overloaded and developed sufficient heat to cause deterioration and breakdown of the cable insulation. Because only a few of the Alpha II and Beta channels were equipped with this type of filament and because they were operated for a very short period of time, no accurate analysis of electrical troubles can be given.

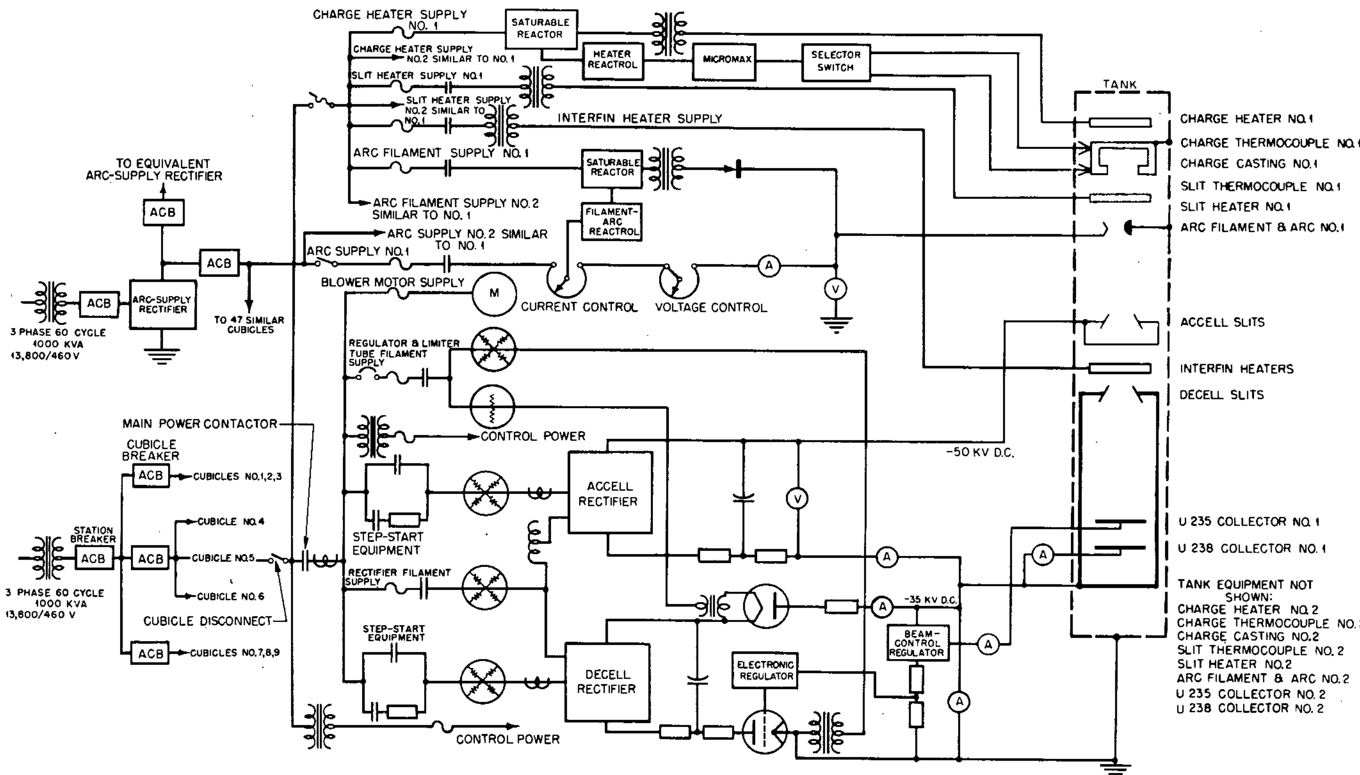


Fig. 11.1 — Diagram of the Alpha I system.

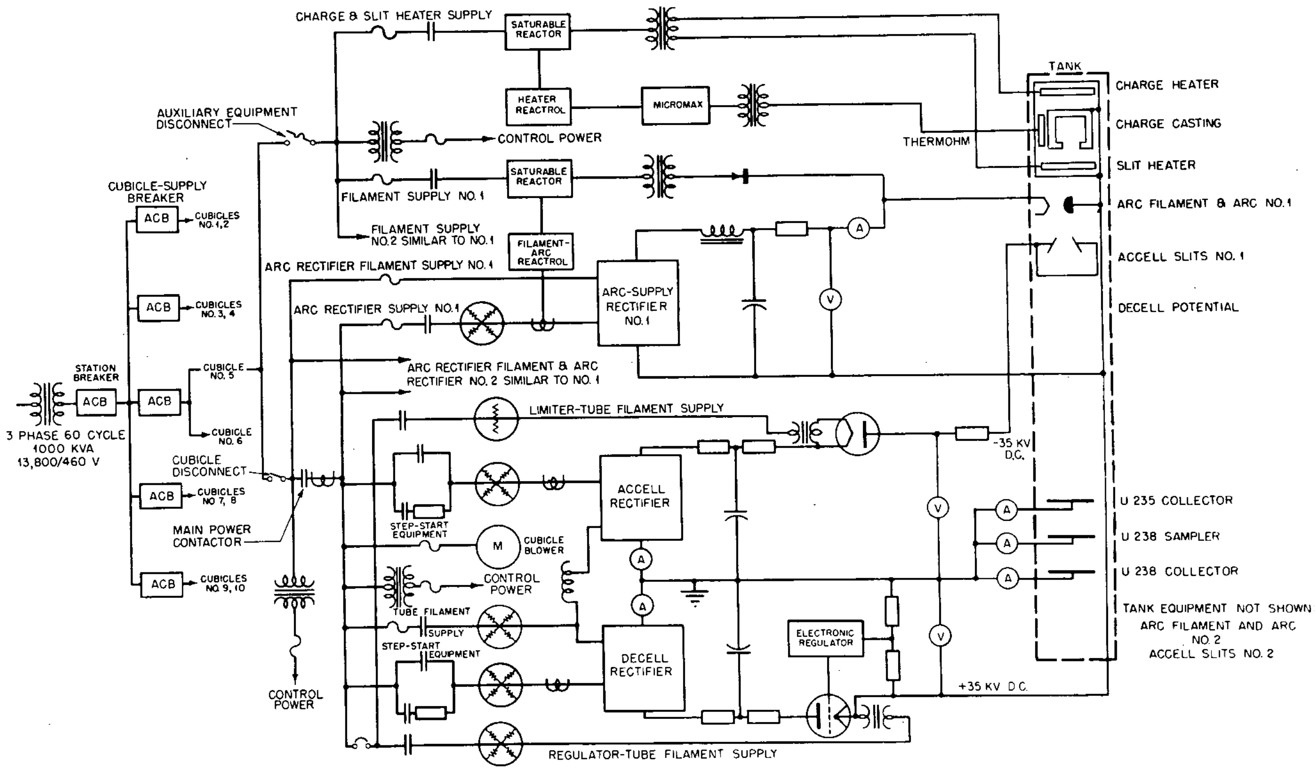


Fig. 11.2 — Diagram of the Beta system.

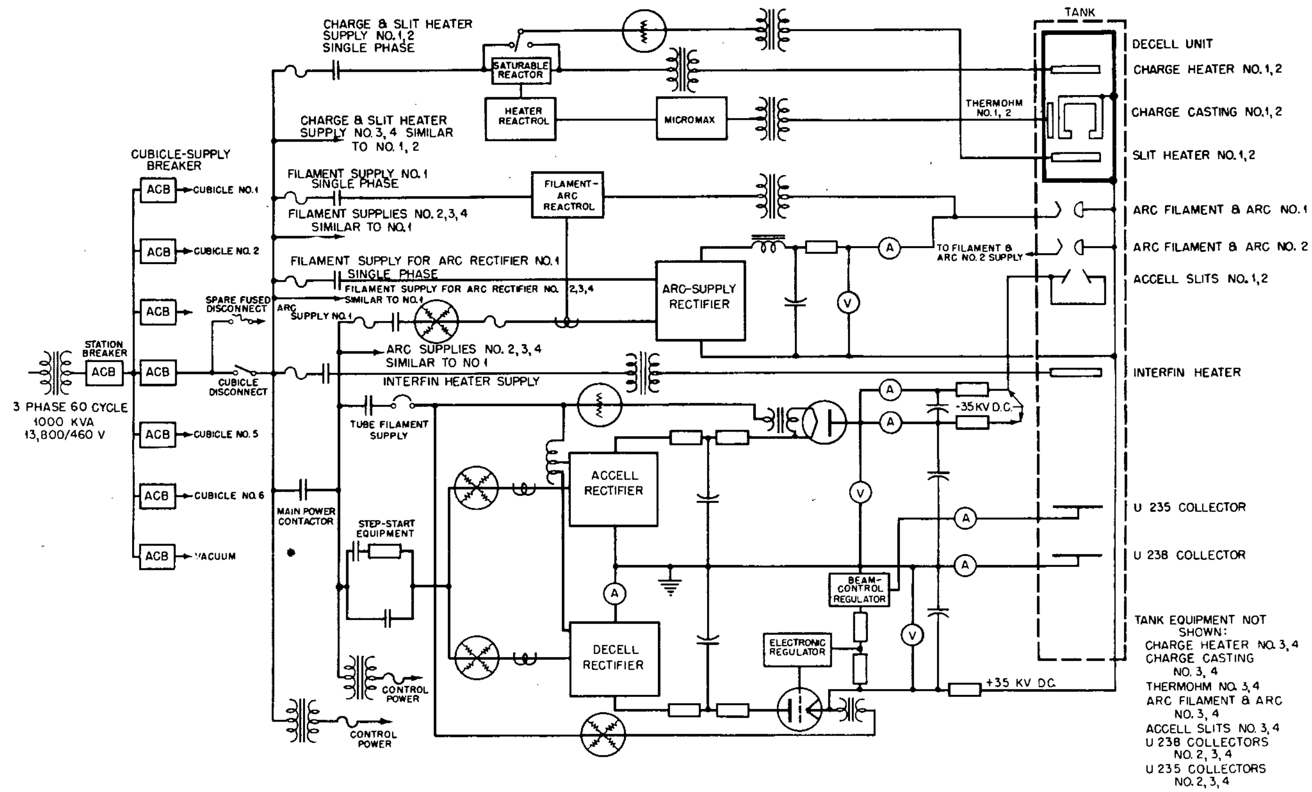


Fig. 11.3—Diagram of the Alpha II system.

Chapter 12

ARC-SUPPLY EQUIPMENT

The arc was the discharge produced by the ionization of the molecules of charge vapor by the action of the electrons emanating from the filament. The potential difference between the filament and the arc chamber and the action of the magnetic field defined the path of the electrons and the position of the arc. The characteristics of the arc were dependent on, among other variables, the potential difference and the arc current.

1. ARC SUPPLIES

The arc supply for Alpha I consisted of a low-voltage multiphase mercury-arc rectifier. Power was supplied to this rectifier from a station service 13,800/460-volt transformer. The mercury-arc rectifier furnished a common arc supply to 48 channels and utilized a common bus for power distribution. This rectifier had sufficient capacity to supply 96 channels and was connected with another equivalent supply so that either supply could be removed from service without interrupting operation. This interconnection was used for maintenance purposes.

From the common-arc-supply bus each channel was supplied with power for two separate arc circuits. These two circuits were identical and supplied power to the arc through a switch, fuse, contactor, current-control rheostat, and voltage-control rheostat. The low-resistance current-control rheostat was used in conjunction with the filament-arc regulator to control the arc current. The high-resistance voltage-control rheostat was used to control the operating voltage of the arc.

The arc supply was rated 200 kw, 300 volts, 2 wire, direct current. It was a model 6RP40CA General Electric sealed-ignitron rectifier. The equipment was stationary and was metal-enclosed in complete units with the individual sections throat-connected. The units con-

sisted of the a-c switchgear and auxiliary control, power transformer, rectifier, and the d-c switchgear. Within the a-c switchgear unit, drawout air circuit breakers and auxiliary control transformers were mounted. This equipment had an a-c voltage range of from 283.0 to 94.4 volts in nine steps equivalent to a rectifier d-c output-voltage range of from 300 to 100 volts. The step changes were made with a load-ratio control mechanism operated by a single handwheel. The main transformer was 3 phase and oil filled, with its primary connected delta and its secondary connected double Y. The transformer was designed to carry 100 per cent load continuously (45°C temperature rise) and 125 per cent of full load for 2 hr or 200 per cent for 1 min.

The rectifier enclosure included sealed ignitrons, the magnetic-excitation equipment, and the water-cooling system. The d-c switchgear unit consisted of a 2-pole drawout air circuit breaker, voltage regulator, alarm and reset relays, d-c voltmeter, and d-c ammeter. A General Electric Diactor or carbon-pile voltage regulator was used for the regulation of the output voltage of this rectifier. This regulator received a signal from the d-c supply line and controlled the voltage of this supply line by varying the phase of the igniter voltage with respect to the positive half cycle of the anode voltage of the rectifier. This action controlled the starting point of the anode current, maintaining an average d-c voltage output.

The Alpha I rectifier was protected on the a-c supply from undervoltage, overcurrent, short circuit, arc-backs, transformer high temperature, and low cooling-water flow. The d-c supply lines were protected from both overcurrent and reverse current. An audible control was utilized to indicate ignitron misfire faults.

The d-c power supply mentioned above was the source of power for the individual arc circuit in the mass spectrograph, with each channel having two identical circuits. Each circuit consisted essentially of a switch, contactor, fuse, two series-connected rheostats, and a load. The switch was rated 10 amp, 600 volts direct current, and the contactor was rated 15 amp, 115 volts alternating current. Three of the 15-amp contacts were connected in series so that the arc at these contacts would be minimized.

The voltage-control rheostat (Fig. 11.1) had two series-connected windings, one winding rated 1 amp, 42 ohms and the second rated 5 amp, 18 ohms for a total resistance of 60 ohms. A mechanical stop was provided so that the resistance could not be decreased below 9 ohms on the 5-amp winding. The current-control rheostat had a total resistance of 18 ohms. It consisted of two series-connected windings, the first being rated 1 amp, 15 ohms and the second 5 amp,

3 ohms. A stop was provided so that the resistance could not be decreased below 1.5 ohms on the 5-amp winding. Both rheostats were operated manually, with the voltage rheostat acting as a voltage drop in the supply line to the arc, and with the current rheostat acting as a signal source to the filament-current regulator. This current was protected from short circuit and overloads by a 4-amp fuse. The arc current was measured by an ammeter. The arc voltage was measured by a voltmeter.

The arc-supply rectifiers for Beta and Alpha II were essentially alike, consisting of two low-voltage rectifier supplies permanently connected for 2-wire operation. The Alpha II supplies (Fig. 11.3) were rated 10 amp, 250 volts direct current, and the Beta supplies (Fig. 11.2) were rated 10 amp, 350 volts direct current. The rectifiers were energized from the cubicle 460-volt main power contactor through fuses, a contactor, an induction voltage regulator, and a signal transformer. The induction voltage regulator and signal transformer were used to control arc voltage and arc current, respectively. The two main rectifier transformers and their associate filament transformers were mounted in the same oil-filled tank with the secondaries, and the rectifiers were insulated for 58 kv direct current to ground. The rectifier used a 6-phase diametrical connection and mercury-vapor tubes for rectification. These rectifier tubes were mounted on the top of high-voltage bushings extending through the top of the transformer case, and the leads from the rectifier plate transformer and the filament transformers were brought out through these high-voltage bushings.

The Alpha II main power transformers were rated 3 phase, 60 cycles, 4.9 kva, 820/282 volts line to neutral. The filament transformers in the same oil-filled tank with the rectifier plate transformer were rated single phase, 60 cycles, 0.297 kva, 460/5.5 volts.

The rectifier panel on top of the high-voltage bushings, extending through the main transformer case, supported the rectifier tubes, resistors, capacitors, and reactors associated with each of the two arc-supply rectifiers. The rectifier tubes used were the General Electric type FG-32 mercury-vapor rectifiers. The FG-32 tube had an inverse anode voltage of 1,000 volts and an average anode current rating of 2.5 amp. The filament circuit of these tubes was rated 5 volts, 4.5 amp, with a minimum cathode heating time of 5 min. Each of the two rectifiers in one unit used six such tubes in a diametrical 6-phase connection.

The d-c output of each of these rectifiers was filtered by two 50-μf capacitors connected in parallel and rated 600 volts, in conjunction with a 10-amp 0.0085-henry filter reactor. This filter was designed

to maintain a minimum ripple voltage on the output of the rectifier equal to 1.0 per cent of the rectifier d-c output voltage. The reactor was shunted by a Thyrite used to protect the reactor against transients reflected from the mass-spectrograph load.

The rectifier tubes were protected from cold-cathode bombardment by an interlock circuit containing a time-delay relay, which prevented the application of anode voltage for a period of 5 min subsequent to the application of filament voltage. This time-delay interlock prevented the anode voltage from being applied before the cathodes of the rectifier tubes reached operating temperature. In Alpha II and Beta the arc rectifiers were protected from overloads by fuses placed in the primary a-c circuit to the main rectifier transformer and also by fuses placed in the d-c circuit to the load. In the Beta circuit 10-amp 600-volt fuses were used in both the 460-volt supply circuit and the d-c output circuit. Alpha II was supplied with 15-amp 600-volt fuses in the 460-volt supply, with 10-amp 600-volt fuses between the induction voltage regulator and the rectifier transformer primary, and with 10-amp 600-volt fuses in the d-c output circuit.

The arc load current and load voltage from each of the individual rectifiers were measured on the d-c side by an ammeter calibrated for 10 amp full scale and by a voltmeter calibrated for 400 volts full scale. These meters, connected directly in the load circuit, were mounted on suitably insulated panels located behind glass windows in the high-voltage cubicles.

2. OPERATIONAL HISTORY OF THE ARC SUPPLY

Alpha I used a common arc supply, supplying 48 individual channels. This arc supply was rated 200 kw, 300 volts at a current rating of 665 amp. It was normally operated with an output of 180 volts and an approximate load of 225 amp. This load increased to 450 amp when one rectifier was taken out of service for maintenance purposes, and the second rectifier was used to carry the normal load of the two individual rectifiers. Even under this condition the rectifier was operated considerably below its rating.

These rectifiers were the source of supply for each of two arc circuits of an Alpha I channel, with each circuit operating with a normal load current of from 2.0 to 2.5 amp. These individual arc circuits were initially protected from overload by 4-amp Superlag fuses. This circuit contained two series-connected rheostats, each rheostat being made of two sections connected in series. The first of these rheostats, the voltage-control unit, was rated 60 ohms total, with one section rated 1 amp, 42 ohms and the second section rated 5 amp, 18 ohms. The second or current-control rheostat was rated 18 ohms total with

one section rated 1 amp, 15 ohms and the other rated 5 amp, 3 ohms. These rheostats employed a stop on the 5-amp section in such a manner that the total circuit resistance could not be reduced to less than 10 ohms. Thus, owing to the position of the rheostat, the total resistance in the circuit could lie between 10 and 78 ohms, and the short-circuit current for this circuit, assuming a 2-ohm supply-line impedance, would lie between 2.2 and 15 amp. For normal operation of 2.0 to 2.5 amp the current-control rheostat was operated on the 1-amp winding near the common point between the 1- and 5-amp windings. The current-control rheostat was operated at 50 per cent of its rating, and the voltage-control rheostat was operated at approximately 225 per cent of normal rating. These rheostats, composed of two sections of widely differing current ratings, were difficult to protect with the 4-amp fuse. Under short-circuit conditions in the arc circuit it was possible to exceed the current rating of the 1-amp rheostat section without exceeding that of the 5-amp section or that of the protective fuse.

The load was subject to a considerable number of short circuits, and when operating at 2.2 amp with a normal voltage of 125 volts, the circuit had 25 ohms in series with the load, thus giving a short-circuit current of 7.2 amp. This value of short-circuit current resulted in so many fuse failures in this circuit that Westinghouse thermal-trip Sentinel breakers using a 4-amp element were installed in the circuit, and the 4-amp fuses were replaced by 10-amp fuses. With this type of protection, and operating under the same conditions as previously described, the majority of the faults were cleared by the thermal breakers.

Experiments were conducted with the Alpha I mass spectrographs in which the arc was operated at currents and voltages higher than in the normal equipment. To prevent interference with plant production all the experimental cubicles operating on this basis were isolated from the common arc supply and were supplied with power from another source. This experimental arc supply utilized a motor-generator set having a maximum d-c output of 300 volts and sufficient capacity to carry 200 per cent of the actual load required by these experimental cubicles. The output voltage was regulated by a General Electric Diactor voltage regulator, which maintained the output voltage to within 1 per cent of the desired value and which was set to hold a bus voltage of approximately 275 volts.

Experimental work was started before the original arc circuit could be revised to handle the increased load. Operating from the 275-volt bus with a load current of from 4 to 6 amp, the high-voltage cubicle control equipment was overloaded under some conditions as much as

600 per cent. This resulted in numerous blown fuses and burned-out contactors, rheostats, and Sentinel breakers. This trouble was remedied by replacing the contactors and fuses with others of ample rating. The Sentinel breakers were replaced by General Electric PJC plunger relays set to trip at 8 amp. The stops were removed on the control rheostats, and resistors were inserted in series with these rheostats so that for normal operation they would operate on the 5-amp winding. Normal operation of these experimental cubicles after the above changes were made was experienced with the arc operated at approximately 200 volts, 4 to 6 amp direct current.

A change in one of the arc supplies of the Alpha I equipment was necessary owing to an installation error made by the contractor. This particular rectifier was found to be susceptible to arc-backs in the ignitron rectifier tubes. An investigation showed that the inductance-capacity filter had been reversed so that this filter presented a capacitive load to the rectifier rather than an inductive load. The charging current for this capacitor exceeded the peak surge-current rating of the ignitron, thus causing these ignitrons to arc back. A reversal of the filter connection to present an inductive load to the rectifier eliminated this trouble, and no further changes were required in any of the Alpha I arc-supply rectifiers.

The arc supplies used in Alpha I had a very good service record, with no failures experienced in either the transformers or sealed-ignitron rectifier tubes. The water interlock switches used on these ignitrons did become defective owing to corrosion and were replaced with an improved type of Fischer and Porter Co. water-flow switch.

The sealed ignitrons used in the Alpha I arc supply, furnished by General Electric, were known from past experience to be subject to frequent water leaks due to corrosion of the stainless-steel water jackets. A similar ignitron had been purchased from Westinghouse to be used as replacement and was available in sufficient quantity so that 25 per cent of the ignitrons in service could be replaced. The General Electric tubes were removed from service prior to any failures and were replaced by the Westinghouse type in order that a life test could be conducted on both types of ignitron tubes. At the end of the Alpha I plant operation neither type of tube had failed.

Alpha II and Beta used an individual arc supply for each ion source, and these were identical in most respects. The Alpha II arc-supply rectifier was rated 250 volts, 10 amp direct current and was actually operated at 150 volts, 3 amp direct current. The Beta rectifier was rated 350 volts, 10 amp direct current and was operated at 180 volts, 3.5 amp direct current. Since all the component parts of the rectifier, including the induction regulator in the primary circuit for voltage

control, had been designed for a normal load greater than the actual operating load, none of the equipment in the Beta or Alpha II arc supply was overloaded. The ratings of the various component elements of these two rectifiers have been tabulated in Tables 12.1 and 12.2, and a comparison has been made between these ratings and the average operating values.

In the Beta and Alpha II arc-supply rectifiers the secondary leads from the rectifier transformer and the filament transformers were brought out through high-voltage bushings and were terminated on a cylinder mounted on this bushing. This cylinder served as a mounting for the rectifier tube assembly. The terminations on the cylinder were made by means of a feed-through stud with nuts, washers, and lock washers on each side of the cylinder. When the leads connected to these studs were removed for maintenance reasons, it was found that the stud became loose, making it necessary to remove the entire rectifier assembly in order to tighten the connection of the back side of the stud.

The Beta arc-supply concentric feed-through conductors from the filament transformer to the rectifier assembly occasionally developed high contact resistance at the filament transformer. There was insufficient room to raise the assembly high enough to correct this condition while the arc supply was in place in the high-voltage cubicles. Thus it was necessary to remove these defective Beta arc supplies from the high-voltage cubicle in order to remove the transformer assembly from the oil-filled tanks so that the filament-transformer connection could be cleaned and tightened. One Beta arc-rectifier supply transformer failed owing to a high-voltage breakdown from the winding to ground within the transformer.

In the Alpha II and the Beta arc-supply rectifiers, trouble was experienced because of the type of overload protection provided. In the Alpha II rectifier, 6-amp fuses were located in the primary circuit. These fuses allowed the short-circuit direct current to reach a value high enough to overheat the stabilizing resistor in the output of the rectifier; these resistors overheated the high-voltage cable supplying the load. To prevent injury to the high-voltage cable the 6-amp fuses were first replaced by 3-amp fuses. It was found that such fuses failed too frequently, and another device had to be tried. The protection adopted consisted of the thermal overload device in one phase and 6-amp fuses in the other two phases of the supply line to the arc rectifier. The thermal element was rated 3 amp and automatically reclosed in approximately 10 sec. This proved successful since it limited the short-circuit current in the d-c supply to a value that would not overheat the stabilizing resistor and that eliminated fuse replacements.

In the Beta arc-supply rectifier, trouble was experienced with the overload protection equipment. Thermal overload breakers equipped with heaters of the correct value for the arc current were installed in the individual d-c arc circuits. The sizes of the fuses in the primary to the rectifier supplies were increased so that they gave protection only against failure of the rectifier equipment and were not blown by short circuits in the individual arc circuits. In later buildings the General Electric Company provided fuses in the d-c circuit between the induction voltage regulator and the transformer and in the 460-volt supply line.

In Beta and Alpha II it was necessary to energize the filament of the arc rectifier 5 min before applying high voltage to the anode. Since these two circuits were interlocked through a time-delay relay, considerable time could be lost if the filaments were not turned on as the first operation in the start-up sequence. Owing to the frequency of start-up and the short length of time required for start-up in the Beta plant, a circuit change was made to provide for the turning on of the rectifier filaments when the high-voltage disconnect switch was closed. This change proved very satisfactory since it simplified operation and ensured against additional start-up time.

In the original Beta arc supply, no high-voltage shield was provided in the rectifier transformer. Considerable trouble was experienced with failure of the FG-32 mercury rectifier tubes because of surges fed back on the high-voltage cable from the mass-spectrograph load. Such surges caused the rectifier tube to arc back and discharge the rectifier filter capacitor. Subsequent to the surge, the peak charging current to this capacitor was of a greater magnitude than could safely be supplied by the FG-32 tubes. To limit this surge current to a safe value, 5-ohm anode resistors were placed in each rectifier tube circuit. After this change, rectifier tube losses were normal.

It was found that the a-c ripple in the output of the Beta arc rectifier was excessive. This ripple occurred because the cathode was tied to one side of the filament and the rectifier return was connected to the opposite side. This condition was corrected by tying the rectifier return to the cathode side of the filament. To make this change it was necessary to rotate the tube socket 90 deg, thereby reversing the filament connection without making it necessary to fabricate new filament-bus connectors.

In Alpha II the arc-rectifier supplies were located in front of ventilators that supplied air to the building. The air from these ventilators was only a few degrees above outside temperature, and on cold days the FG-32 tubes used in these rectifiers were cooled below their normal operating temperature. As a result the tubes failed to conduct,

thus causing unstable operation of the arc-supply rectifiers. This condition was corrected by Stone & Webster by the installation of deflectors, which caused the air to be blown downward on the transformer rather than upon the tubes. In Alpha II and Beta the current-limiting resistors in the arc-supply rectifier operated within their rating for steady-state current. However, these resistors tended to overheat and fail owing to surges since they acted as line-terminating resistors and, in Alpha II, caused other failures that were even more severe. The Alpha II resistors were mounted directly under the high-voltage arc-supply cable, and overheating of these resistors would tend to melt the insulation of the cable. The melted insulation would drop on the resistors and the composition board on which they were mounted, usually starting a fire that would burn the mounting board, the resistors, and the cable. Transite boards were placed above and below the resistors to keep the mounting board and cable from overheating.

But for a normal number of burned-out meters, very little trouble was experienced with the arc-supply metering circuits, except in the Beta equipment. Here the d-c ammeters and voltmeters for measuring the arc-supply output were mounted on an insulated panel operated at a potential of approximately 39 kv direct current with respect to ground. One side of the arc supply was tied to this high-voltage panel and the decell rectifier supply. The meters were insulated from the panel for the potential of the arc supply. It was found that this insulation was not sufficient, and a large number of the ammeters were burned out because of sparking between the meter movement and the panel. An attempt was made to correct this condition by the use of a large insulating sleeve, which provided a larger air gap between the meter and the panel. This served the purpose for an appreciable length of time, but changing operating conditions caused recurrence of the meter failures. Further protection against surges was provided for these meters by by-passing such surges directly from the arc-supply line to the meter panel through capacitors mounted directly at the ammeter terminals.

The same surges were also causing failures in the oscilloscope used to check the ripple on the arc voltage. A neon tube was connected across the input terminals to the oscilloscope to protect the input of this instrument from such surges.

In Beta, four 20-ohm resistors, connected in parallel to give an effective resistance of 5 ohms, were connected in series with the arc supply and the load. When the 5-ohm anode resistors were added, two of the series load resistors were removed to make the effective value of the resistance of this portion of the circuit 10 ohms. This was done to reduce the surge short circuit of the arc rectifier. The same value

of series resistance in the d-c circuit from the arc rectifier was maintained in later buildings, even though the rectifier transformers in these buildings were equipped with high-voltage shields.

A similar change was made during operation of the first Alpha II building, and by General Electric in the later Alpha II buildings. In the last two Alpha II buildings the deciding factor in making this change was that General Electric was unable to supply sufficient resistors for the equipment prior to the start of operation.

The voltmeters and ammeters used in the arc circuit were connected to the Beta arc-supply rectifier by a short length of concentric high-voltage cable having an external ground shield. The voltmeters and ammeters were mounted on an insulated meter panel inside the high-voltage cubicle. Trouble was experienced with this short length of meter-connecting cable owing to a breakdown between the external ground shield and the internal high-voltage leads. Since this cable was located inside the high-voltage cubicle and access could not be gained to it if the high-voltage circuits were energized, cable failures were overcome by removing the ground shield and suspending this short length of jumper cable by standoff insulators.

Table 12.1 — Alpha II Arc-supply Rating of Component Parts Compared to Load

Equipment	Rating	Load or operating condition
Rectifier transformer	60 cycles, 3 phase, 4.9 kva, 820/282 volts (line to neutral), 3.45 amp (primary)	0.96 kva, 335 volts (line to neutral), 1.7 amp (primary)
Filament transformer	60 cycles, single phase, 0.297 kva, 460/5.5 volts, 0.64 amp (primary)	0.27 kva, 420 volts, 0.64 amp (primary)
Rectifier tube	Maximum peak inverse anode voltage, 1,000 volts; filament voltage, 5 volts; filament current, 4.5 amp; plate current, 2.5 amp	Maximum peak inverse anode voltage, 236 volts; filament voltage, 5 volts; filament current, 4.5 amp; plate current, 0.5 amp
Filter choke	0.0085 henry, 10 amp, 250 volts direct current	3 amp, 150 volts direct current
Resistor	20 ohms, 150 watts	90 watts
Capacitor	50 μf, 600 volts direct current	150 volts direct current

Table 12.2—Beta Arc-supply Rating of Component Parts Compared to Load

Equipment	Rating	Load or operating condition
Rectifier transformer	60 cycles, 3 phase, 4.9 kva, 820/282 volts (line to neutral), 3.45 amp (primary)	1.05 kva, 580/200 volts (line to neutral), 1.1 amp (primary)
Filament transformer	60 cycles, single phase, 0.297 kva, 460/5.5 volts, 0.64 amp (primary)	0.27 kva, 420/5 volts, 0.64 amp (primary)
Rectifier tube	Maximum peak inverse anode voltage, 1,000 volts; filament voltage, 5 volts; filament current, 4.5 amp; plate current, 4.5 amp	Maximum peak inverse anode voltage, 418 volts; filament voltage, 5 volts; filament current, 4.5 amp; plate current, 0.6 amp
Reactor	0.0085 henry, 10 amp, 250 volts direct current	3.5 amp, 180 volts direct current
Resistor	20 ohms, 150 watts	135 watts
Capacitor	50 μf, 600 volts direct current	180 volts direct current

Chapter 13

FILAMENT-ARC REGULATORS

The production of ions in the arc is only the beginning of the mass-spectrograph process. This is followed by the acceleration of the ions out of the arc chamber and their travel through space in the magnetic field until they are finally focused on the receiver as separate isotopes. The interrelation of these parts is such that they must all be controlled individually in order that maximum production may be realized. To obtain a sharp process for maximum reception at the receiver it is necessary that the origin be sharp. The sharp origin is obtained by varying the conditions of the arc serving as the origin, through control of arc voltage, arc current, and other variables. Thus control of arc current and voltage is important.

1. DESIGN OF THE FILAMENT-ARC REGULATOR

It was essential that the arc current and arc voltage be independently adjustable. This was accomplished by operating the filament of the arc source emission-limited. The emission-limit current value of the filament was controlled by a regulator known as the "filament-arc regulator." An input signal to the regulator, proportional to the arc current, produced an output signal of suitable phase and magnitude to operate a control device in the ion-source filament circuit. This control device adjusted the filament emission so as to maintain a constant arc current. Since the filament-arc regulators maintained a constant-voltage source, it was possible to adjust either arc current or arc voltage independently.

A block diagram of the Alpha I filament-arc regulator is shown in Fig. 13.1. Figure 13.2 is the block diagram of the type of regulator used in Alpha II and Beta. Such a regulator can be divided into the following components:

1. Signal rectifier
2. D-c voltage amplifier

3. Power amplifier
4. Filament-control device
5. Filament transformer
6. Filament rectifier (except in Alpha II)
7. Filament

The signal source provided a signal proportional to the arc current. The d-c voltage amplifier was used to amplify the arc-current signal to a magnitude large enough to operate the power amplifier. This power amplifier operated the filament-control device. The filament transformer provided the low-voltage high current necessary to operate the ion-source filament and in Alpha I and Beta operated with the filament rectifier.

A simplified schematic diagram of the Alpha I filament-arc regulator is shown in Fig. 13.3. The arc-current-signal source consisted of a rheostat R_1 connected in series with the ungrounded negative lead from the arc supply. The voltage drop across this resistor was held constant by the regulating action of the system. The value of arc current was determined by the amount of resistance in the rheostat R_1. The voltage drop across this rheostat, proportional to the arc current, was compared to a standard voltage in the d-c voltage amplifier, and the difference in voltage between the signal and the standard was applied to the grid of tube V_1. The output signal from V_1 was then applied through a voltage divider to the grid of V_2 and further amplified. This amplified signal was then applied to the input circuit of the power amplifier. This power amplifier consisted of a full-wave grid-controlled rectifier whose load was the d-c winding of a 3-phase saturable reactor. The grid-control voltage of the power amplifier consisted of two signals: a fixed-phase shift voltage and a variable d-c bias supplied by the d-c voltage amplifier.

By this method the d-c current in the saturable reactor was made inversely proportional to the arc current. Since the saturable reactor was connected in series with the primary of the filament transformer, the filament current depended on the degree of saturation of the saturable reactor. A decrease in arc current through the action of the d-c voltage amplifier and the power amplifier tended to increase the d-c current in the winding of the saturable reactor, thus increasing the current in the ion-source filament.

Since the ion-source filament was operated emission-limited, an increase in this current tended to raise the emission-limit value, increasing the arc current, which increased the voltage drop across R_1. The reverse occurred when the signal voltage across R_1 increased, and owing to the regulating action of this system the voltage drop

across R_1 was held constant. Because this regulator system tended to maintain a constant voltage drop across R_1, a change in the resistance value of R_1 effectively changed the operating value of the arc current. The rheostat R_2 was used to control the voltage across the arc; and since the voltage drop across this resistance was not included in the regulator loop and since the arc current was dependent only on the drop across the signal resistor R_1, the voltage across the arc was adjusted by means of R_2 without changing the operating current of the arc.

The Beta filament-arc regulator operated similarly to the Alpha I regulator. A simplified schematic diagram of the Beta filament-arc regulator is shown in Fig. 13.4. In Beta, insulating transformers were used to allow a major portion of the regulator proper to be near ground potential. The required points of insulation were between the primary and secondary winding of the arc-supply rectifier transformer and between the primary and secondary of the filament transformer.

In Beta the signal source consisted of current transformers in series with the primary of the arc rectifier transformer. The current-transformer secondary was connected to a suitable vacuum-tube rectifier, which gave a d-c signal proportional to the a-c current drawn by the arc supply. A rheostat R_1 was connected across the secondary of the current transformer to load this transformer, adjusting the ratio between the a-c line current and the d-c signal supplied by the rectifier. This rheostat provided manual control of the arc current. Three such rectifier combinations were supplied, one located in each phase of the 3-phase supply to the arc rectifier transformer. The output voltages of these three rectifiers were combined to give a composite signal proportional to the current in the 3-phase supply line. The rheostat, shown as R_1 in the simplified schematic diagram of Fig. 13.4, consisted of three rheostats operated in tandem with each rheostat connected across the secondary of one of the transformers in the supply line.

The d-c amplifier, the power amplifier, and the 3-phase saturable reactor were essentially the same as in Alpha I. Since it was desirable to have an arc-voltage control operated at ground potential, the voltage control for Beta consisted of an induction voltage regulator placed in the 460-volt supply line ahead of the current transformers that formed the signal source.

The Alpha II filament-arc regulator was similar to the regulator used in Beta. A simplified schematic diagram of this regulator is shown in Fig. 13.5. Insulation of the regulator was provided at the

same points as in Beta. The arc-voltage control and the arc-signal sources were also the same. The d-c voltage amplifier for the Alpha II regulator differed from the Beta amplifier only in that low-frequency degenerative feedback was supplied for each of the two stages of amplification. This degenerative feedback tended to prevent hunting in the regulated arc current. An output-voltage limiting diode was provided in the Alpha II regulator. The power amplifier for the Alpha II regulator consisted of a grid-controlled full-wave rectifier. The Alpha II power amplifier was used to supply voltage pulses to the grids of two thyratrons connected back-to-back. These two thyratrons were connected in series with the primary of the average filament current.

Table 13.1 has been compiled to show the relative ratings of the component parts of the filament-arc regulator. These data compare the signal source, voltage amplifier, power amplifier, and filament-control device for the Alpha I, Alpha II, and Beta processes.

2. OPERATIONAL HISTORY OF THE FILAMENT-ARC REGULATOR

In the original Beta high-voltage cubicles the cable that carried the arc-supply d-c output, as well as the decell supply voltage, entered the cubicle and looped over the arc-signal rectifier so that during surges a voltage was induced in the signal circuit. This induced voltage was of sufficient magnitude to arc over from plate to plate at the tube base and to destroy the rectifier tube in this circuit. The induced voltage in the signal rectifier was due to a current in the loop caused by the discharge of the decell line-terminating capacitor. This current passed through the cubicle wall from the point at which the capacitor was grounded to the point at which the high-voltage cable was grounded. This loop was completed by the high-voltage cable passing over the top of the signal rectifier and tying to the line side of the terminating capacitor. To eliminate this current loop the high-voltage cable was rerouted along the cubicle wall on the opposite side of the signal rectifier, and the ground terminal for this cable shield was tied directly to the point at which the terminating capacitor was grounded.

The original filament-arc regulator was equipped with 5Y3 tubes in the signal-rectifier circuit. The 5Y3 is a directly heated cathode rectifier, and when a filament failure occurred, it was accompanied by a filament-to-anode short, shorting out the secondary of the signal-current transformer associated with this tube. This resulted in the loss of signal voltage to the filament-arc regulator, tending to cause this regulator to increase the filament current to the maximum value.

Since this shortened the life of the filament, it was necessary to prevent the filament current from being driven to the maximum value whenever a signal-rectifier tube failed. This was accomplished by substituting a 5V4 in place of the previously used 5Y3. The 5V4 is an indirectly heated cathode rectifier, and filament failure of this tube would not cause filament-to-anode shorts, which result in a loss of signal voltage. With the use of the 5V4 the signal voltage would only be decreased by that portion contributed by one phase of the signal rectifier, with the remaining signal rectifiers in the other two phases still supplying some signal voltage. The 5V4 tubes were substituted for the 5Y3 type in the signal rectifiers in the Alpha II and Beta arc-supply equipment.

The 5Y3 tubes were also used as rectifier tubes in the power supply of the voltage amplifiers. In this service filament failures with the resulting filament-to-anode shorts resulted in short-circuit currents that destroyed the power transformers. The 5V4 tube was substituted in this class of service in place of the 5Y3. This tube substitution was made for both the Alpha II and Beta processes.

The arc-voltage adjustment for Alpha II and Beta was accomplished by induction voltage regulators connected on the line side of the rectifier transformer. In Beta the arc-voltage adjustment was extremely critical for proper operation. These regulators did not give a sufficiently fine control of this voltage. A series resistor was inserted in the common leg of the induction-voltage-regulator motor circuit; this resistor limited the current and reduced the starting torque of this motor. It was then possible, by rapidly opening and closing the control switch, for the regulator motor to accomplish small adjustments in the arc voltage. The resistor used was a slide-wire type since it was necessary to adjust the value of the resistor to compensate for differences in the friction of the bearings and gears in the regulator drive. In Alpha II the arc operating potential was not so critical as that in Beta, and hence this change was made only in the Beta supplies.

The original ion-source filament used in Beta had an extremely short life; in fact, this filament usually would not last through a production run. A change was made in the filament-arc regulator in an attempt to increase the life of the ion-source filament. A circuit was designed and installed which changed the value of the signal resistor in the filament-arc regulator circuit to reduce the filament current to a minimum whenever the arc voltage was turned off.

To accomplish this an experimental installation making use of the signal circuit of the regulator as a primary element was tried. Since the signal voltage was proportional to the arc current, the voltage

would drop when the arc was extinguished from any cause. A normally closed contact of a voltage relay, the coil of which was wired across the signal circuit, dropped out when the arc was extinguished. This relay energized an auxiliary relay, which disconnected the signal to the d-c amplifier and inserted the signal-control rheostat in series with the filament-supply saturable reactor. This limited the current flow to the reactor and lowered the filament current. The rheostat made it possible to adjust the filament current manually to the value necessary to restrike the arc. When the arc was restruck, the current flowing in the primary of the signal-control transformer would induce a voltage in the signal circuit that would pick up the sensitive voltage relay and restore the circuit to normal. This experiment provided the essential circuit for a filament "lifesaver" and also additional control over the filament current. Later developments in filament designs alleviated the problem of short life to the extent that a plant change was not considered economical.

The filament-arc regulators for each of the three processes had been designed to operate at higher current and voltage than the actual values used in plant operation; therefore none of this equipment was overloaded.

The signal source for the filament-arc regulators was a continual cause of trouble in Alpha II and Beta. The signal control consisted of three rheostats operated in tandem and connected across the secondary of the signal transformers. These rheostats were constructed so that it was possible to turn the movable arm past the end of the resistance winding, and when this occurred, it was impossible to bring this arm back on the winding by means of the rheostat control knob. Attempts to turn the rheostat back to normal operating position usually resulted in breaking the rheostat. To overcome this fault it was necessary to install stops on the face of the control panel to engage the heavy pointer attached to the control knob. Before this change was made, the number of failures of these rheostats was extremely high.

In Alpha I the arc-voltage control rheostat, rather than the current-control rheostat, was the cause of the major portion of failures in this circuit. The current rheostat, normally operated at less than 50 per cent of rating, had a failure rate that was essentially zero; however, the voltage rheostat, normally operated at 225 per cent load, had a failure rate of 4 per cent per month. This was not considered excessive because of the overload and the large duty cycle imposed on them. A higher rated rheostat could have been substituted but was undesirable because of its greater physical size.

The potentiometers used for the maximum adjustment setting of the Alpha II filament-arc-regulator amplifiers were failing at an extremely high rate. This potentiometer was rated 50,000 ohms, 2 watts, and was connected across a 210-volt circuit. Although this was within the operating rating of the potentiometer, after a period of time the value of resistance of the potentiometer would drop with a corresponding increase in power dissipated by the potentiometer, causing its failure. The number of such failures became so great that, for a period of time, it was impossible to obtain sufficient replacements. As an emergency measure it was necessary to lower the voltage across this potentiometer. Wire-wound potentiometers were ordered and were installed in most units by the time of the Alpha II shutdown.

The type 2051 thyratron tubes used in the power amplifier of the filament-arc regulator for Alpha II had a high failure rate. These tubes were operating with a grid voltage of −150 volts maximum, but the rating of these tubes was −100 volts maximum. A test of 100 tubes showed that approximately 10 per cent ionized and fired when the grid voltage reached −125 volts. A GL-502 thyratron was suggested as a replacement for the 2051 tube. This tube had the same characteristics as the 2051 with the following exceptions: The maximum grid-voltage rating was −200 volts instead of −100 volts, and the tubes had a metal instead of a glass envelope. The metal envelope of this tube was connected to the cathode and in the power amplifier would be at a potential of 105 volts from ground. It was thought that these tubes would not be satisfactory because the physical construction of this power amplifier was such that maintenance personnel could come into contact with the metal envelope and receive painful shocks. The General Electric Company also suggested that a $\frac{1}{25}$-watt neon lamp be installed from the grid to the cathode of the tube, but this also was undesirable since it added more components to an already complicated circuit.

The solution to the problem consisted in reducing the maximum grid voltage from −150 to −100 volts. This reduction was accomplished by connecting a 2-megohm resistor between the cathode and grid of the 2051 tube. Since the original circuit used a 1-megohm resistor in series with the grid, the addition of this 2-megohm resistor formed a voltage divider that reduced the maximum grid-to-cathode voltage to a value of −100 volts.

General Electric FG-172 tubes were used in the filament-control device. Two such tubes were used in a back-to-back circuit, and the failure rate of the tube in the right-hand socket was approximately 2.8 times that of the tube in the left-hand socket. Investigation dis-

closed that it was necessary to phase the heater circuit of the FG-172 tube properly relative to its respective anode circuit. The necessity for phasing was due to the construction of the tube. Since the heater was not completely enclosed by the cathode, it contributed to the effective potential gradient between cathode and grid. In Alpha II the phase relation of the filament of the right-hand tube to its anode supply was different from that of the left-hand tube. This phase relation was reversed, and the number of tube failures was reduced.

Table 13.1 — Rating of Filament-arc-regulator Equipment in Alpha I, Alpha II, and Beta

Equipment	Alpha I	Alpha II	Beta
Signal source	Rheostat: 18 ohms total; two sections in series, one section 15 ohms, 1 amp, the other section 3 ohms, 5 amp; stop on 5-amp section at 1.5 ohms	Current transformer: 60-cycle 20-va 200- to 100-amp primary, 4- to 17.5-amp secondary with three intermediate taps Rectifier (5Y3 tube): peak inverse voltage, 1,550 volts; peak anode current, 675 ma; average anode current, 225 ma Rheostat: 3 gang, 25 ohms, 50 watts per phase	Current transformer: 60-cycle 20-va 200- to 100-amp primary, 4- to 17.5-amp secondary with three intermediate taps Rectifier (5Y3 tube): peak inverse voltage, 1,550 volts; peak anode current, 675 ma; average anode current, 225 ma Rheostat: 3 gang, 25 ohms, 50 watts per phase
Voltage amplifier	6SJ7 and 6SN7 tubes: gain, 50	6SJ7 and 6SN7 tubes: gain, 50	6SJ7 and 6SN7 tubes: gain, 50
Power amplifier	FG 17 tube: peak inverse voltage, 5,000 volts; peak anode current, 2.0 amp; average anode current, 0.5 amp	2051 tube: peak inverse voltage, 700 volts; peak anode current, 375 ma; average anode current, 75 ma	FG 17 tube: peak inverse voltage, 5,000 volts; peak anode current, 2.0 amp; average anode current, 0.5 amp
Filament-control device	Saturable reactor: 3 phase, 60 cycles, 3 kva, 265 volts alternating current; 125 volts direct current (50 and 75% taps)	Two FG 172 tubes (connected back-to-back): peak inverse voltage, 750 volts; peak anode current, 77 amp; average plate current, 2.5 amp	Saturable reactor: 3 phase, 60 cycles, 3 kva, 265 volts alternating current; 125 volts direct current (50 and 75% taps)

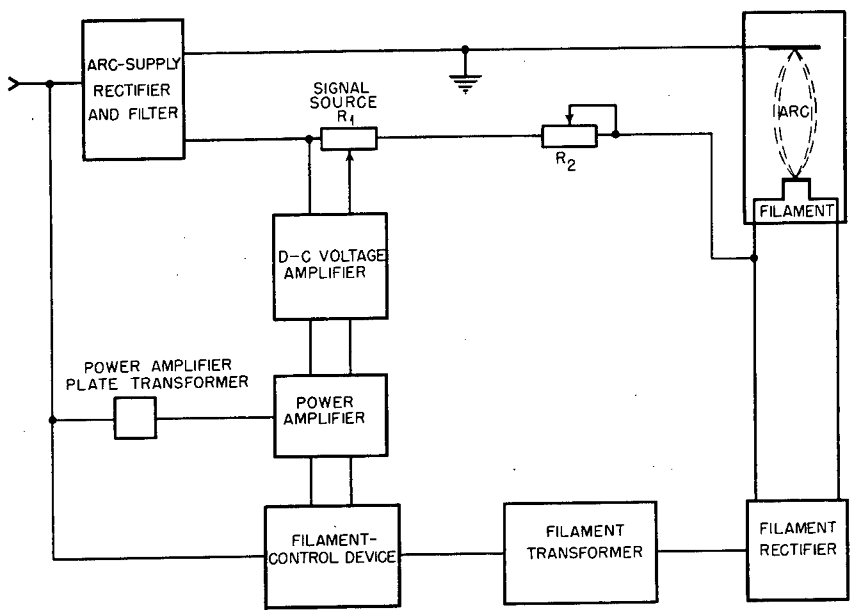


Fig. 13.1—Block diagram of Alpha I filament-arc regulator.

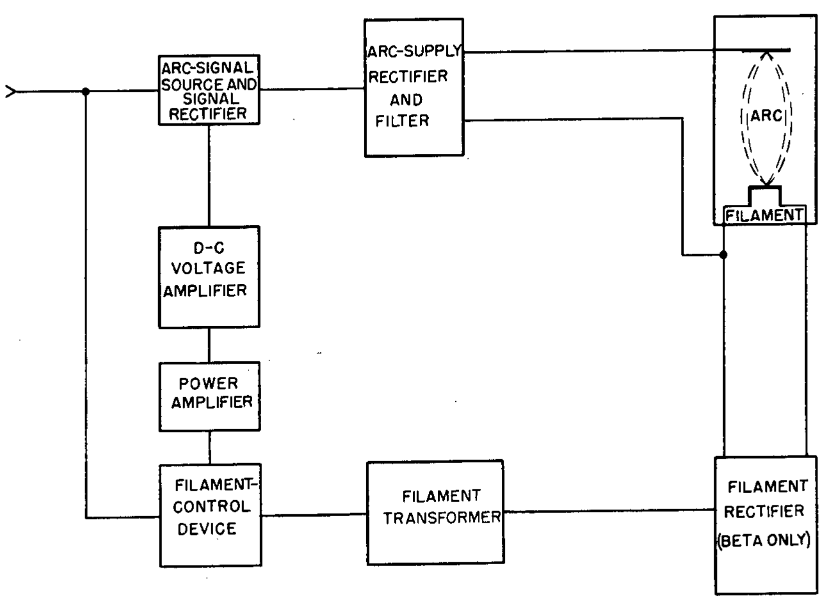


Fig. 13.2—Block diagram of Alpha II and Beta filament-arc regulator.

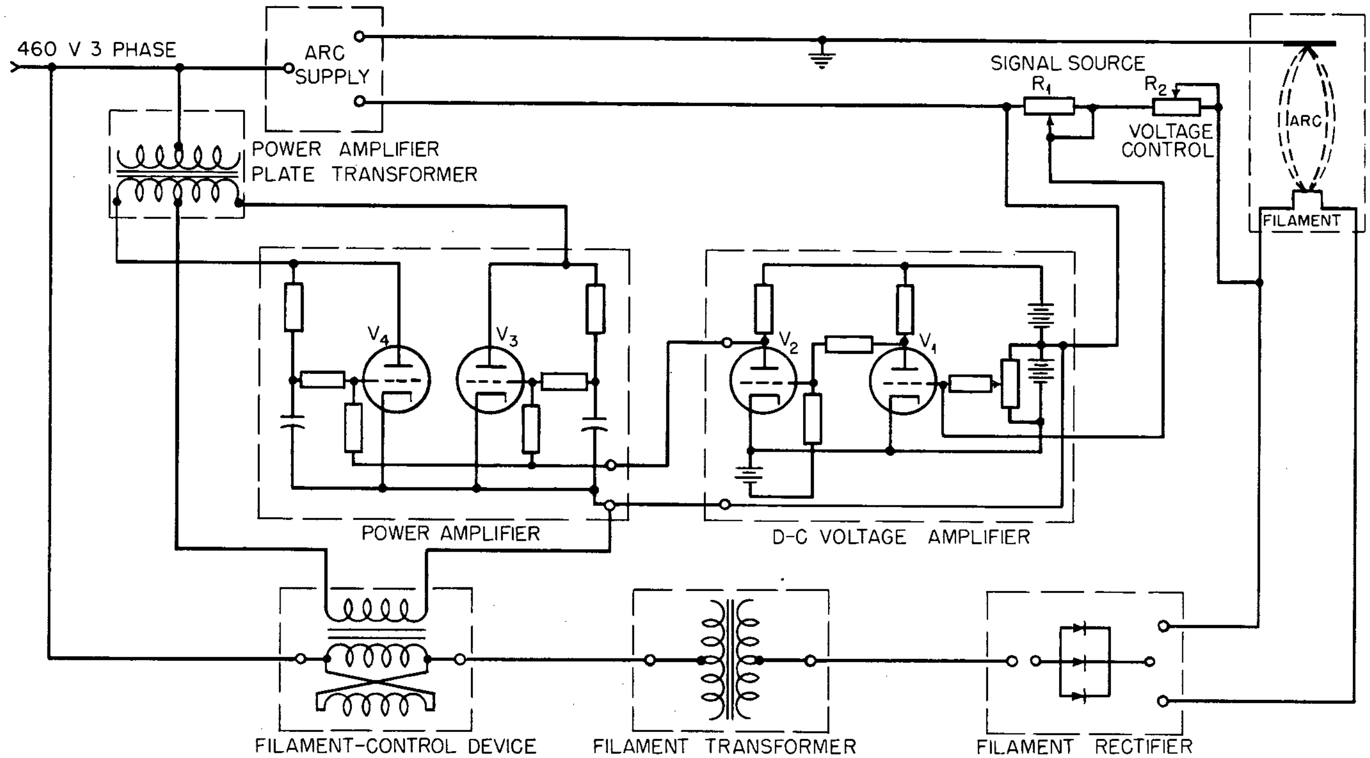


Fig. 13.3—Simplified schematic diagram of Alpha I filament-arc regulator.

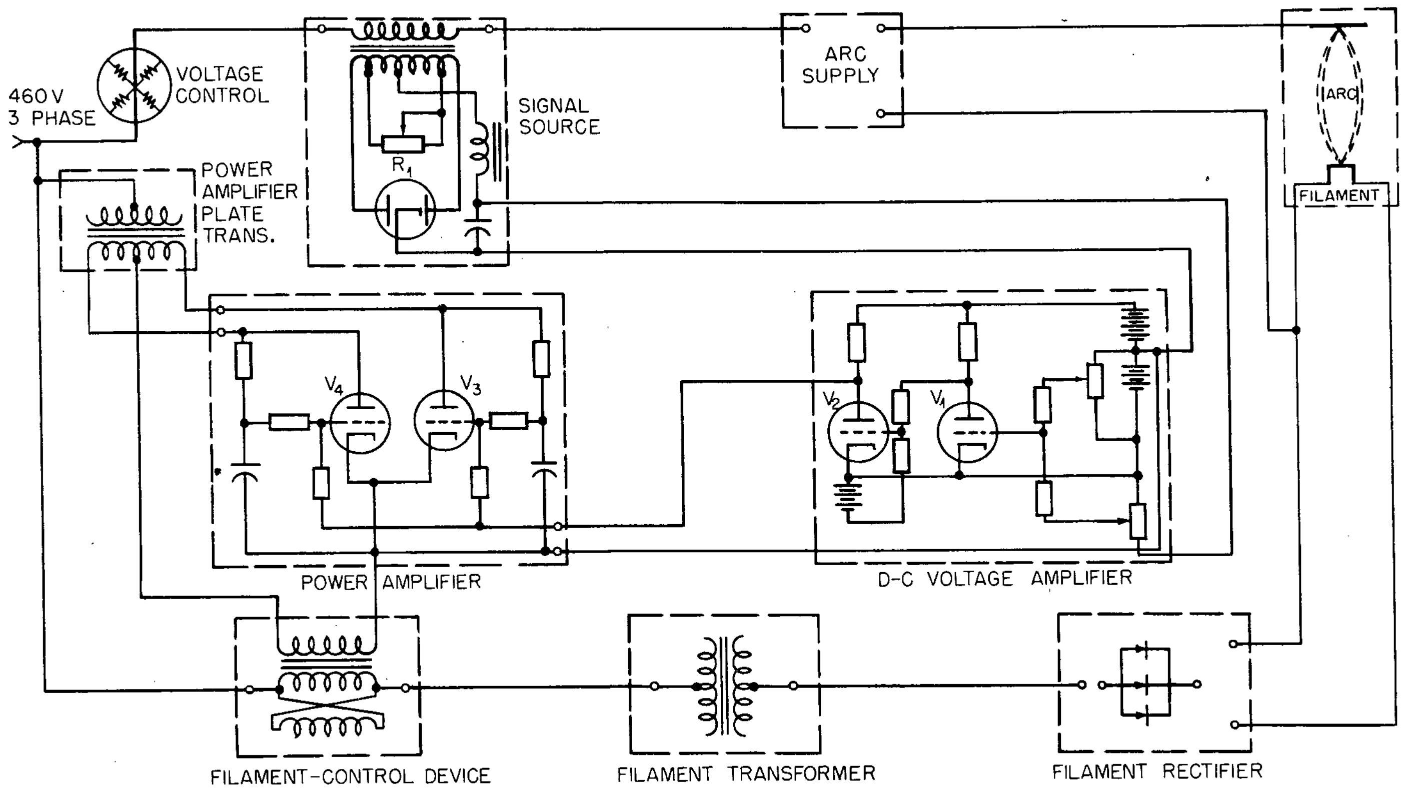


Fig. 13.4—Simplified schematic diagram of Beta filament-arc regulator.

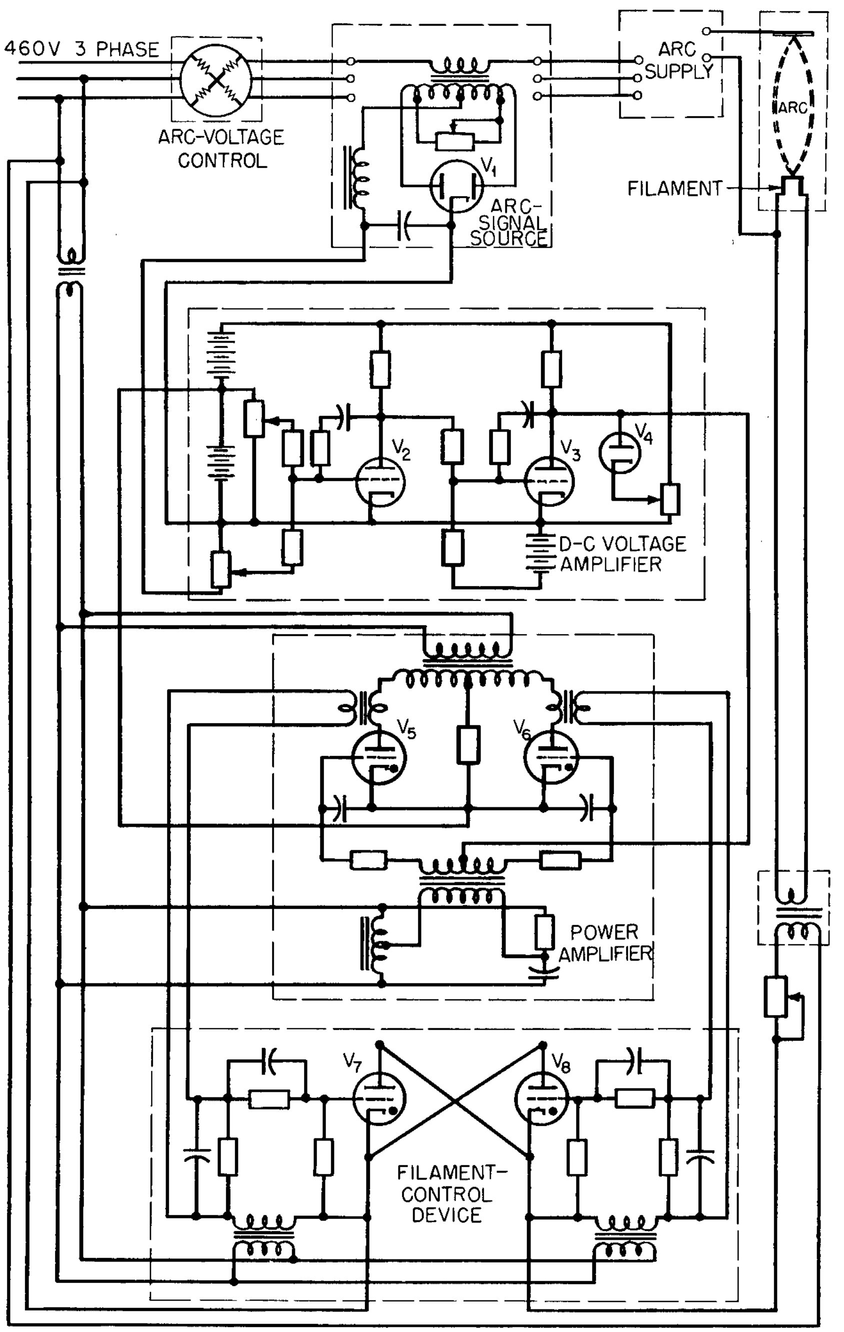


Fig. 13.5—Simplified schematic diagram of Alpha II filament-arc regulator.

Chapter 14

ION-SOURCE HEATER SUPPLY AND CONTROL EQUIPMENT

The mass spectrograph included a charge-sublimation chamber, an arc chamber, and an ion-accelerating-electrode system. All these parts were operated at temperatures in excess of 450°C. One group of electric heaters provided heat to vaporize charge material (usually UCl_4) in the sublimation chamber; another group of heaters provided heat to prevent condensation of vaporized charge material in the arc chamber; and in certain plant applications a third group of heaters provided heat in the accelerating-electrode region.

Various control devices associated with the heater circuits included recording Micromax or Bailey Pyrotron controllers, thermocouples, and Thermohms to control the heat delivered by the heaters and to maintain required temperature differences between the parts, principally between the arc and sublimation chamber.

1. HEATER SUPPLIES

1.1 Charge-heater Supplies. In Alpha I the charge heater was supplied with single-phase power from the heater-cubicle 460-volt 3-phase bus. The charge-heater circuit was energized by a 25-amp 600-volt contactor, which fed a saturable reactor acting as a variable impedance to the transformer. The transformer was rated 60 cycles, single phase, 2.5 kva, 430/100 volts. The saturable reactor used in this circuit was rated 60 cycles, 2.5 kva, 460 volts alternating current, 80 volts direct current, 0.45 amp maximum direct current. The overload protection for this circuit consisted of 10-amp fuses in the 460-volt supply line.

In Alpha II the charge and arc-chamber heaters were supplied from a common 460-volt bus through fuses rated 20 amp, 600 volts and through a 25-amp contactor. The charge-heater transformer, rated 60 cycles, single phase, 2 kva, 460/60 volts was supplied through a saturable reactor rated 60 cycles, single phase, 6 kva, 460 volts al-

ternating current, 125 volts direct current, 0.55 amp maximum direct current. A switch was provided so that the arc-chamber heaters could be supplied from either side of the reactor. In Beta the charge heaters and the arc-chamber heaters were supplied from a common 460-volt bus in the heater cubicle through 15-amp 600-volt fuses and through a 25-amp contactor. The charge-heater and arc-chamber-heater transformers were connected in parallel and were supplied from this contactor through a saturable reactor rated 60 cycles, single phase, 4 kva, 460 volts alternating current, 79 volts direct current, 0.6 amp maximum direct current. From this reactor the charge heaters were supplied through an insulating transformer rated 60 cycles, single phase, 2 kva, 415/100 to 70.5 volts in eight steps and insulated for 58 kv direct current.

1.2 Arc-chamber-heater Supplies. The arc-chamber heaters for the Alpha I ion sources were supplied with single-phase power from the heater-cubicle 460-volt 3-phase bus. This circuit was energized by a 25-amp 600-volt contactor supplying power to a step-down transformer, which supplied the arc-chamber heaters. This transformer was rated 60 cycles, single phase, 4 kva, 460/100 to 50 volts with six intermediate steps. The circuit and the heaters were protected from overload by 10-amp fuses in the 460-volt supply line.

The arc-chamber heaters for Alpha II were supplied by an insulating step-down transformer energized through an induction voltage regulator rated 1.56 kva, 440 ± 249 volts, single phase, 6.25 amp. The induction voltage regulator, by suitable switching, could be connected to either side of the saturable reactor in the charge-heater circuit. The induction voltage regulator in the arc-chamber-heater circuit set the differential temperature between the arc-chamber heaters and charge heaters. The transformer was rated 60 cycles, single phase, 4 kva, 460/60 volts and was insulated for 58 kv direct current. This transformer and the charge-heater transformer were mounted in a common oil-filled tank, with the connections from the secondary of these transformers to their respective heaters being made by potheads and high-voltage cable.

The insulating transformer, which supplied power to the arc-chamber heaters in Beta, received its power through the same saturable reactor used in the charge-heater circuit and through an induction voltage regulator. The induction voltage regulator controlled the differential temperature of the heaters and was rated 60 cycles, single phase, 2.34 kva, 415 volts, 5.63 amp. This regulator supplied the arc-chamber insulating transformer, which was rated 60 cycles, single phase, 2 kva, 415/100 to 70.5 volts in eight steps and was insulated for 58 kv direct current. The arc-chamber-heater transformer and charge-heater

transformer were mounted in a common oil-filled tank with their secondaries connected to the heaters by potheads and high-voltage cable.

1.3 Interfin-heater Supplies. The interfin heaters for Alpha I were supplied with power from the heater-cubicle 460-volt 3-phase bus. The heater circuit was protected from overload by 10-amp fuses. The circuit was energized by a 25-amp 600-volt contactor, through which power was supplied to an insulating step-down transformer, which supplied the heaters. The transformer was rated 60 cycles, single phase, 4 kva, 460/100 to 70.5 volts with seven intermediate steps and was insulated for 35 kv direct current.

The Alpha II interfin heaters were supplied from the heater-cubicle 460-volt bus through 20-amp 600-volt fuses and through a 25-amp contactor. This circuit supplied power to a transformer rated 60 cycles, single phase, 6 kva, 460/80 volts.

Owing to the smaller size and the difference in construction of the Beta ion source, no interfin heaters were required.

2. TEMPERATURE-CONTROL EQUIPMENT

2.1 Micromax Temperature Controller. The indicating temperature controller furnished for Alpha I was a standard model C Micromax having a range of 0 to 600°C and using a chromel-alumel thermocouple. Copper and constantan wires were used between the thermocouple in the charge-holder casting and the Micromax in the heater cubicle. The temperature indicator installation in Alpha I was relatively simple since it operated at ground potential.

For Alpha II and Beta a model S Micromax made by Leeds & Northrup Co. was used as the basic unit. The model S Micromax was an indicating and recording single-point continuous-line curve-drawing controller. Normal applications of this instrument used a d-c resistance bridge, one leg of which consisted of a temperature-sensitive resistance known as a "Thermohm." However, because the charge-heater casting and the Thermohm operated at a potential above ground equal to the decell voltage, a special design was employed which used an a-c resistance bridge and an a-c insulating transformer in the Thermohm circuit.

The Thermohm was a platinum wire having a resistance of 8.88 ohms at 20°C and 19.102 ohms at 350°C. The Thermohm did not follow the standard platinum calibration curve but was 1.2 ohms lower in resistance at all temperatures. The change in resistance was not linear, this nonlinearity at 450°C amounting to approximately 1 per cent full scale.

The Thermohm was connected by a 1 to 4 ratio insulating transformer to the bridge circuit of the Micromax. To measure the change in Thermohm resistance through the insulating transformer it was necessary to compensate for the insulating-transformer reactance to give this leg unity power factor. If no compensation were provided for the reactance of the insulting transformer in the Thermohm arm of the bridge, the galvanometer would indicate a voltage even though the voltage drops in all arms of the bridge were otherwise balanced. To achieve a unity factor an 8.5 μf capacitor was placed across the bridge terminals of the insulating transformer. This value of capacitance caused the transformer-Thermohm combination to resonate at 60 cycles, presenting a resistive circuit to the Wheatstone bridge in the Micromax.

It was necessary to excite this transformer with constant voltage since core loss, which may be represented as a resistance, varies with the applied voltage. Any variation in the core-loss equivalent resistance would produce inaccuracies in the temperature-measuring device. Caution had to be exercised to prevent the transformer core from accidentally becoming magnetized during trouble shooting, testing, etc., since this would change the magnetizing current and the effective core-loss resistance.

The equivalent circuit of the transformer-Thermohm combination is shown in Fig. 14.1. A linear change in Thermohm resistance would still give a nonlinear change in the total transformer and Thermohm resistance. This nonlinearity of the equivalent resistance of the transformer-Thermohm combination is in the same direction and greater than the inherent nonlinearity of the Thermohm alone. These characteristics have been exaggerated ten times in Fig. 14.2. If it were possible to decrease the combined transformer and Thermohm resistance as the center scale position of the Micromax is approached, linearity could be achieved. This was accomplished by reducing the voltage applied to the transformer at center scale, which reduced the core loss and its equivalent resistance. The amount of voltage reduction required was determined by experiment to be 4.7 per cent. The change in resistance of the transformer-Thermohm combination for full scale (350 to 550°C) was 42 ohms.

Summarizing the preceding paragraphs, the following conditions must be met by the bridge:

1. The voltage to the transformer must be constant (equal at both ends of the scale).

2. For linearity the voltage supplied must be reduced 4.7 per cent at center scale.

3. The full-scale change in resistance of the transformer-Thermohm combination must be 42 ohms.

4. At 350°C the resistance of the transformer-Thermohm combination must be 220 ohms.

The equivalent bridge circuit is shown in Fig. 14.3. The resistance R_1 of the transformer-Thermohm combination will increase 42 ohms full scale, and R_2 will also increase 42 ohms because S, which is 42 ohms, is added to R_2 at 550°C. If S_1 has one-half the resistance of S and is mechanically coupled to S, then, at 350°C, R_4 plus 42 ohms equals R_3 plus 21 ohms, and at 550°C, R_4 plus 21 ohms equals R_3. If R_2 is made greater than R_4 by 21 ohms, the resistance of the upper arms of the bridge will always be equal. Since the resistances of the lower arms are also equal, the voltage drops in all arms are equal. It should be noted that S is a main slide-wire and that S_1 serves to keep the voltages balanced. The slide-wire K was provided to reduce the voltage applied to the bridge by 4.7 per cent at center scale to compensate for the transformer-Thermohm combination nonlinearity. The use of the slide-wire K is not practical since it would have a peculiar motion in that it would travel from zero ohms at the ends of the scale to a maximum at the center of the temperature scale. This was solved by replacing the star connection formed by S and K with its delta equivalent, as shown in the final bridge circuit of Fig. 14.4.

In the final circuit of the Micromax several changes and additions had been made. The slight voltage increase, resulting from the change in IR drop in the primary of the transformer as the Thermohm resistance increased, produced an increase in the core-loss equivalent resistance. This resulted in a slight increase in the total transformer equivalent resistance, the change being equivalent to an error of 0.1 per cent at 550°C. This change had been compensated for by increasing the resistance of R_3 from 161.0 to 161.2 ohms.

For convenience in manufacturing, the slide-wire S was shunted. Since no current is drawn by the galvanometer at balance, this is identical to a single unshunted slide-wire. S_2 and K_2 have been added without changing the 220-ohm resistance of the R_2 arm of the bridge. This was done so that S_2 might be used to match the bridge to the transformer-Thermohm combination resistance R_1.

Three conductors were carried to the transformer so that the lead resistances would be added to the two arms equally and would not be measured. The galvanometer used the third lead connected to the transformer terminal.

The rheostat H, which shunted the galvanometer, was approximately 180 ohms. This was the galvanometer sensitivity adjustment providing maximum sensitivity without instability.

The nonlinearity of the transformer-Thermohm combination, approximately 6°C at center scale, was corrected by reducing the voltage 4.7

per cent, which amounted to 1 per cent error per volt change in the supply.

The voltage stabilizer supplied was a commercial model designed to give constant voltage at a rated load greater than the actual bridge load. This condition resulted in a rise in regulated voltage with a decrease in supply voltage. Linear decrease was corrected by adding a portion of the unregulated voltage to the regulator output. For this purpose a transformer with a ratio of 110 to 16 was connected as a booster to the output of the voltage stabilizer. This resulted in a constant-voltage output characteristic for the load employed.

The bridge circuit of the Micromax was energized with 4 volts supplied by a center-tapped transformer, and a control slide-wire was positioned in the bridge circuit on the same shaft with S_1 and S (Fig. 14.4) to regulate the current supplied to the heaters. The tap on the control-circuit slide-wire was positioned manually by a knob on the front panel of the Micromax case. This control was arranged so that when the temperature pointer and the indicator on the control dial were the same the bridge would be balanced. An increase or decrease in the controlled temperature would result in a rotation of the control slide-wire and cause an unbalance of the bridge. A voltage, whose phase and amplitude depended on the direction of unbalance, appeared across the temperature-controller output terminals and was applied to a General Electric Reactrol system. This system caused the temperature of the charge to be readjusted until it was again equal to the temperature of the control-setting dial. The indicated scale range of the Micromax recorder was 350 to 550°C. A diagram showing the relation between the control slide-wire in the Micromax and the General Electric Reactrol heater control panel is shown in Fig. 14.5. The model S Micromax, using an a-c bridge, was used as a temperature indicator in the Alpha II channel and in 144 of the Beta channels.

2.2 Bailey Pyrotron Temperature Controller. The remaining 144 Beta channels were equipped with the Bailey Pyrotron, an a-c bridge-type instrument for measuring temperature by employing a Thermohm as the temperature-sensitive element. This instrument used a modified Wheatstone bridge, as shown in Fig. 14.6. In this bridge circuit the measuring slide-wire was placed between two resistors A and B so that, as the contact moved downward on S, resistance was subtracted from the A side and added to the B side. In this way the bridge was balanced by adjusting the ratio of the bridge arms rather than by changing the resistance of one arm, as is normally done in a Wheatstone bridge circuit. The advantage is that the slide-wire contact does not carry bridge current, and its resistance does not affect the calibration. The Pyrotron bridge is in balance when the

$$\text{Ratio} = \frac{B + S\theta}{A + S(1 - \theta)} = \frac{T}{R}$$

where θ is the position of the contact on the slide-wire as a function of full travel (θ varies from 0 to 1). The values of A, B, S, and R are chosen so that the minimum and maximum values of T correspond to the end points of the slide-wire-contact travel. Although the relation between the slide-wire rotation θ and the measured temperature is not linear, this relation was corrected by properly shaping the cam, which drives the indicating pointer and recording pen, so that the temperature-indicating scale was linear.

The Bailey Pyrotron recorder-controller was designed to operate with the same type of Thermohm as was used with the Micromax temperature indicator. The Thermohm circuit was insulated from the Pyrotron by an insulating transformer.

The measuring bridge circuit of the Pyrotron differed somewhat from the standard Bailey resistance-thermometer circuit. A special circuit was necessary to compensate for the self-inductance of the insulating transformer and to minimize the harmonic unbalance produced by its magnetic iron core. The schematic diagram of the Pyrotron (Fig. 14.7) shows the method used for compensating for changes in ambient temperature of the lead wires, the addition of shunt resistance across the slide-wire, and details of the motor-control circuit. By the use of three lead wires to the Thermohm and by a proper choice of bridge resistors, the effect of line resistance on calibration was held to less than 0.25 per cent error regardless of the scale position; however, unbalance in the lead resistance caused by poor connections could produce large errors.

The Bailey Pyrotron used an electronic amplifier with the bridge circuit, the function of which was to detect and amplify voltage produced by an unbalanced condition in the bridge measuring circuit. The amplifier output was applied to a motor-control circuit to operate the slide-wire drive motor in the direction required to rebalance the measuring circuit. The complete amplifier unit consisted of an amplifier section, a power-supply section, and a motor-control section on the main controller cabinet.

The d-c power-supply unit consisted of a full-wave rectifier using a 6X5 vacuum tube and a capacitor-resistance filter. The schematic diagram of this power supply is shown in Fig. 14.8.

The voltage amplifier was a class A amplifier of conventional design, consisting of two stages of resistance-coupled amplification. A 6SL7 amplifying tube consisting of two triodes had a voltage amplification factor of approximately 2,500. As a result a 0.001 volt unbalanced signal from the measuring circuit produced an output voltage of 2.5

volts applied to the motor-control circuit. Since the slide-wire drive motor responded to a voltage as low as 1.0 volt input to the 6N7 motor-control tube, the drive motor was sensitive to about 0.004 volt input to the amplifier. The schematic diagram of the voltage amplifier is shown in Fig. 14.9.

For a balanced condition of the bridge circuit the output voltage to the grid of the first triode is zero, and no a-c voltage appears across the amplifier output resistor. When the measuring circuit is unbalanced owing to a temperature change of the Thermohm, an a-c voltage having a magnitude proportional to the amount of unbalance and a phase relation to the line voltage depending on the direction of the unbalance is impressed on the grid of the first tube in the amplifier. This voltage is amplified by the two-stage amplifier and appears as an output voltage across the output potentiometer of the amplifier. The amplifier output voltage will be in phase with the input voltage.

The amplifier output voltage is applied to the motor-control circuit controlling the direction of rotation and speed of the reversing motor driving the slide-wire in the bridge circuit. A schematic diagram of this motor-control circuit is shown in Fig. 14.10. The direction of rotation of the motor is controlled by two saturable reactors, A and B. A 6N7 double-triode tube controls the direct current through the d-c windings of these reactors.

The motor is a capacitor-run type, having two identical windings, which are 90 electrical degrees apart on the stator. The direction of rotation of the rotor is determined by the phase relation of the current in these two windings; therefore its speed with constant load is proportional to the magnitude of the currents in the two windings and to their phase displacement. The motor is of a special design to permit rapid braking when the winding currents are brought into phase. The supply voltage for this motor circuit was boosted to 160 volts from the normal 115-volt source by an autotransformer connected to the primary winding of the supply transformer. This additional voltage compensated for drop through the saturable reactors to obtain rated power from the motor.

The voltage supplied to the 6N7 plate circuit must be from the same source and must have the same phase as the voltage-amplifier grid-input signal. For this application the source was the same supply to which the motor was connected.

Since the voltages on the two plates of the 6N7 are 180 deg out of phase and the grids are in phase, the plate currents of the two sections of the tube are selectively controlled by the phase relation between the grid voltage and the plate voltage. With the bridge balanced, giving a zero-input signal to the two triodes, these tubes conduct about

80 per cent of their maximum plate current. Under this condition the two reactors A and B have equal d-c control currents and have equal inphase currents flowing from the line through the motor windings. These inphase winding currents prevent the motor from rotating.

When the bridge circuit is unbalanced by a change in Thermohm resistance in a direction producing a grid voltage in phase with the plate voltage of triode A and 180 deg out of phase with the plate voltage of triode B, the plate current of B becomes zero and that of A reaches its maximum value. The d-c signal in the saturable reactor B causes the impedance of this reactor to reach a minimum value. The flow of current through the motor circuit is from the line through reactor A into the motor winding W_1 and through the capacitor into winding W_2. The current in winding W_2 leads the current in winding W_1 by nearly 90 deg, and the motor rotates in a negative or counterclockwise direction.

As the motor drives the slide-wire contact to rebalance the bridge circuit, the grid-voltage signal to the motor-control circuit is gradually reduced. When the slide-wire moves to within 1 per cent of the balance point, the plate current in triode B has increased and that in triode A has decreased until they have become equal. In this region of control, considerable braking action is exerted on the motor since the phase displacement between the motor-winding currents approaches zero. In a similar manner an unbalance in the bridge circuit, producing a grid-voltage signal in phase with the plate voltage of triode B, will cause the motor to rotate in the opposite direction. The sensitivity of this system is sufficient to develop approximately 75 per cent of the maximum motor torque with approximately a 0.002-volt input to the voltage amplifier.

The temperature-control circuit used in the Bailey Pyrotron consisted of two slide-wires arranged in a bridge circuit and energized by 50 volts obtained from a step-down transformer. The control slide-wire was actuated by the same motor used to drive the measuring-circuit slide-wire. The control-setting slide-wire was manually set by a knob on the front of the recorder case. The slide-wires were so arranged that when the chart pen and the indicator on the control dial indicated the same temperature the bridge was balanced. A change in the control temperature resulted in a rotation of the control slide-wire and caused an unbalance of this bridge. A voltage whose phase was dependent on the direction of unbalance appeared across the output terminals of a General Electric Reactrol system controlling the power supply to the charge heater. The indicating scale range of these recorders was 350 to 550°C. A diagram showing the relation between the control slide-wire of the Bailey meter and the General Electric

Reactrol heater-control panel is shown in Fig. 14.11. Figure 14.12 is a simplified wiring diagram of the special Bailey Pyrotron recorder.

2.3 Reactrol Control System. To control the current in the resistance heaters and thus to control the charge temperature, a General Electric Reactrol control system was used with either the Micromax or Bailey temperature-control instruments. The current in the heaters and the voltage appearing across these heaters were controlled by the saturable reactor connected in series with the primary of the heater transformer and the power-supply line (Fig. 14.13). The d-c supply for the saturating winding of the reactor was obtained from a rectifier consisting of a thyratron tube and a mercury-vapor diode tube. Power from the control transformer T_5 was supplied in half-cycle pulses through a control thyratron to the d-c winding of the saturable reactor. The energy stored in the saturable reactor, owing to its inductance, caused current to flow through the mercury-vapor diode during the half-cycle period when the thyratron was not passing current. Thus a full-wave rectified current flowed in the d-c winding of the saturable reactor. The grid potential of the thyratron was the vector sum of two voltages known as the "turn-off" and "turn-on" voltages. These two voltages determined the average amount of power flowing in the d-c winding of the saturable reactor.

The turn-on voltage caused the potential of the grid of the thyratron to become positive, allowing it to pass maximum current. This was the voltage appearing across the combination of capacitor A and resistor A because of the rectifying action of the triode section of the 6SN7 tube. This was essentially a d-c voltage due to the long time constant of capacitor A and resistor A compared with the supply-system frequency. The output voltage from the triode section of the 6SN7 was dependent on its grid voltage derived from transformer T_3. This transformer was energized from a network consisting of the tapped secondary of transformer T_1, the position-coarse adjustment, the position-fine adjustment, the sensitivity adjustment, and the potentiometer in the temperature-control instrument.

The turn-off voltage was derived as follows: As the d-c current in the saturable reactor increased, the impedance of this reactor decreased, causing the heater current to increase and the feed-back transformer T_2 to charge the capacitor B through the diode section of the 6SN7 tube to a higher value. The polarity of the voltage across the capacitor B would be opposite to that across capacitor A, and if the voltage of capacitor B was higher than that across capacitor A, negative potential would be applied to the grid of the thyratron. Because of the negative potential applied to its grid, the thyratron would

stop conducting. This would increase the impedance of the saturable reactor and reduce the heater current. However, the time constant of capacitor B and its discharge resistor B was small compared with a half cycle of the supply frequency, and the voltage across this combination produced phase control of the thyratron. As the heater current approached the correct value, the thyratron, owing to this phase control, finally conducted only sufficient current to maintain a heater voltage corresponding to the grid voltage of the 6SN7 tube.

The turn-on, turn-off, and anode voltages for a typical condition of the thyratron, when its grid voltage is more positive than the critical value, are shown in Fig. 14.14.

The five potentiometers in the Reactrol circuit have the following applications:

1. Minimum-adjustment potentiometer; used for initial circuit adjustment.

2. Maximum-adjustment potentiometer; used to determine the maximum primary current in the heater transformer.

3. Sensitivity adjustment; controls the sensitivity of the Reactrol and determines the amount of temperature change required to change the heater current from maximum to minimum.

4. Position-coarse and position-fine potentiometers; determine the position of the operating bands in the temperature-control instruments. These potentiometers are used for the initial alignment of the temperature-indicating pointer and the temperature-setting pointer in the temperature-control instruments.

The network that feeds the transformer T_3 of Fig. 14.13 and the associate thyratron control functions in the following manner: The power to the heater can be gradually decreased from full on, corresponding to maximum direct current in the winding of the saturable reactors, to a low value corresponding to zero current. This is done primarily by the movement of the slider over a sector of the control slide-wire in the temperature-indicating instruments. Thus a movement of the slider in a direction corresponding to a temperature lower than the desired value causes the power to the heater to increase and vice versa. The width of the operating sector, where maximum and minimum heater currents occur, is the difference in temperature indicated by the temperature-indicating pointer and by the temperature-setting pointer in the control instruments. This width can be adjusted by moving the sensitivity control toward position 1 on its dial or by selecting a higher voltage tap on T_3, which increases the voltage applied to the position-coarse- and position-fine-adjustment potentiometers and to the control slide-wire on the temperature-control instruments. The sensitivity of the thyratron control is increased by narrow-

ing the width of the operating sector and is decreased by widening this sector. The location of the operating sector can be changed by the position-coarse position-fine adjustment.

3. HEATER CUBICLE

The arc supply, filament supply, filament-arc regulators, and the heater equipment were either associated with what was known as the "heater cubicle" or located in the cubicle.

The Alpha I heater cubicle was 4 ft wide, 7 ft 6 in. high, and 6 ft 8 in. long and was constructed of light-gauge steel and channel iron. The sides and top were open, and the front and back formed vertical panels, which were used as control panels and for mounting the equipment associated with the cubicle. The cubicle was divided on a vertical plane by a panel extending from the rear control panel approximately 4 ft into the cubicle proper. The two sections of the cubicle thus formed were used to house heater-control equipment associated with two high-voltage channels. The equipment associated with one channel was to the left of the dividing line, and that associated with the second channel was to the right.

On the left-hand side of the front panel was mounted, in order from top to bottom, a Micromax, Reactrol control, a second Micromax, and a second Reactrol control. The upper Micromax and Reactrol control were used to control the charge heater for one ion source. A duplicate combination directly below was used to control the second ion source of one channel. This combination was duplicated on the right-hand side of the heater-control front panel for the second high-voltage channel.

A meter and selector switch were mounted in the center of the front control panel. This meter was used to measure the charge-heater and arc-chamber-heater currents for both channels controlled by the heater cubicle.

On the corresponding half of the rear control panel two filament-arc Reactrols were mounted along with the power-disconnect switch for this half of the heater-control cubicle. This equipment was duplicated on the second half of the rear control panel, and between the two sets of equipment there was located a meter and selector switch used to measure the primary current to the four filament supplies associated with this heater-control cubicle.

The vertical panel extending down the center line of the cubicle was used as a mounting for the various transformers, relays, saturable reactors, and fuses associated with the cubicle. The insulating transformer used in conjunction with the interfin heaters was located on the floor in front of this vertical panel.

The two filament supplies associated with each high-voltage cubicle were located just behind the heater cubicle. All the heater equipment was located on the floor directly below the high-voltage-cubicle floor. The arc supply common to a group of cubicles was located on the heater-cubicle floor.

The Alpha II heater cubicle was located in the high-voltage cubicle with which it was associated, occupying the lower right-front section of the cubicle. The space occupied was approximately 4 ft wide by 3 ft deep. This heater cubicle could be entered through double front doors, which allowed access to the equipment located inside the heater cubicle. Located just above the cubicle doors were the two Micromax controllers used to control the charge heaters. Located above these controllers were meters used to measure the primary current of the transformers that supplied the interfin heater, the arc-chamber heaters, and charge heaters. Selector switches were provided to insert these meters into the desired circuits.

Inside the heater cubicle and mounted on hinged panels were the charge-heater Reactrols and the filament-arc regulators. On the back wall of the heater cubicle were the various relays and fuses associated with the heater circuits. The interfin heater transformer was on the floor of the heater cubicle, but the arc-chamber insulating transformer, the charge-heater insulating transformer, the filament-supply insulating transformer, and the Thermohm insulating transformer were outside the cubicle.

The Beta heater cubicle was similar to that of Alpha I in physical construction and in that one such heater cubicle supplied two channels (except that in Beta no center panel was included). The Beta heater cubicle was approximately 4 ft wide, 5 ft long, and 7 ft 6 in. high.

Mounted on the front panel of the Beta heater cubicle in order from top to bottom were the Micromax and the Reactrol controls associated with the charge heaters of one channel. Directly below this combination were a voltmeter and selector switch used to measure the primary voltages of the charge-heater and arc-chamber-heater insulating transformers. On the back of this panel were mounted the two filament-arc regulators associated with one channel. All the equipment mounted on the left-hand side of the panel was duplicated on the right-hand side. A meter and selector switch were mounted between the four filament-arc regulator; and the meter was used to measure primary current in the four filament-supply rectifiers.

Mounted on the back of the rear panel of the Beta heater cubicle were the cubicle disconnect switch, the various fuses and relays, and the supply transformer and saturable reactor associated with one

channel. This equipment was duplicated on the front of the rear panel for the second channel.

The Beta heater cubicles were located on the floor directly below the high-voltage-cubicle floor, but the filament-rectifier supplies were located directly under the mass-spectrograph units. The charge-heater insulating transformer and slit-heater insulating transformer were combined in a common oil-filled tank and, with the Thermohm insulating transformer, were located directly below the mass spectrograph with which they were associated.

4. CHANGES IN HEATER SUPPLY AND CONTROL EQUIPMENT

4.1 Arc-chamber Induction Regulators. Operating conditions in Beta required that the differential temperature between the arc chamber and the charge be corrected as runs progressed, and since the transformers originally supplied for this equipment had tap switches that could not be changed under load, it was necessary to provide an auxiliary for such differential temperature adjustment. An induction voltage regulator was installed in the load side of the saturable reactor in the line to the arc-chamber-heater transformers. By the time these regulators were installed, it was found that the differential settings initially provided gave the desired regulation. As a result the upper and lower limit switches of the induction voltage regulator were set at the same point, and this regulator was no longer used for operational adjustment but could be used in place of the tap switch originally provided on the transformers.

4.2 Removal of Interfin Heaters. After a short period of operation in both Alpha I and Alpha II the interfin heaters were found unnecessary. In Alpha I the high-voltage cable supplying power to these heaters was disconnected and grounded, thereby eliminating one possible source of high-voltage breakdown. The supply fuses were removed from the circuit used in Alpha II so that the transformers feeding these heaters could not be energized.

4.3 Parallel Operation of Heaters. In Alpha I the arc-chamber heaters, being closely associated with the charge heater and not automatically controlled, often affected the temperature of the charge, causing too much vapor to be evolved. The charge and the arc-chamber heaters were paralleled so that both heaters would be controlled by the temperature-indicator and temperature-control equipment. In addition both heaters were supplied with power from the original charge-heater supply, and use of the arc-chamber-heater supply was discontinued. This arrangement gave very good operating results and was satisfactory electrically because the equipment had sufficient capacity to handle the increased load.

4.4 Beta Heater Equipment. In Beta the charge heater and the arc-chamber heater were turned on simultaneously. During operation it was found necessary to bring the arc-chamber temperature up before the charge heaters were turned on. A wiring change was made utilizing the arc-chamber-heater contactor and its associate control switch to turn on the arc-chamber heaters first and later to switch to a second position that energized both the charge and arc-chamber heaters.

4.5 Heater Ground Return. The heaters in Alpha I were connected in the mass spectrograph with one lead, depending on the ground circuit for its current return. The ground return at the tank utilized two copper buses held together against a wooden support by wood screws. This junction of the two copper buses offered a high-resistance contact in the heater circuit. This resistance was lowered by tightly clamping the buses with machine screws.

4.6 Spark-surge Filters. In Alpha II, transients due to sparking in the high-voltage circuit were picked up by the Thermohm circuit in the temperature-indicating system. A filter circuit was installed to eliminate such transients. This change had not been completed in all the Alpha II channels at the time of the Alpha plant shutdown.

4.7 Differential Thermocouple. The differential thermocouple supplied for Beta provided two thermocouples, one located in the charge casting and the second located adjacent to the arc electrodes. Data on the differential temperatures between these two points were required to obtain curves for determining optimum operating conditions. These data were obtained by wiring the thermocouples in series opposition and using a millivoltmeter to read the differential voltage. By-pass condensers were placed across the meter to take care of high-voltage transients. The meter was mounted on a high-voltage standoff insulator enclosed in a metal-clad case provided with a viewing window. High-voltage cables were used as connections between the mass spectrograph and the differential-temperature meters. Only 36 Beta channels were so equipped, and after curves and sufficient data were obtained to determine correct operating settings for the desired differential temperatures, these instruments were disconnected and left in a stand-by condition for future experiments.

4.8 Thermocouple Switch. The Micromax used as the temperature indicator in Alpha I was initially equipped with a momentary-transfer switch so that an indication of arc-chamber temperature could be obtained. During operation this temperature indication was found to be of little importance; therefore the equipment, which included the momentary switch, was removed from service.

4.9 Bailey Bridge Circuit. In the Beta buildings where the Bailey Pyrotrons were used a change in the value of the capacitors was made in the bridge circuit to compensate for the inductive reactance of each of the Thermohm transformers. This required checking each instrument with its associate Thermohm transformer. Where the combination was found to be out of resonance, the correct value of capacitance was substituted.

4.10 Continuously Energized Bridge Circuits. In Beta the temperature-measuring bridge circuit could easily be turned off. This was undesirable because it required from 24 to 120 hr for the Thermohm transformer circuit to stabilize when reenergized after having been deenergized for any appreciable length of time. This unstable condition resulted from small changes in the inductance of the Thermohm transformer windings and from the residual magnetism of the low-flux-density transformer core. This residual magnetism was determined by the current at the instant the transformer was turned on or off. The power-supply circuit to the temperature-measuring bridge was reconnected so that this circuit was energized continuously. After this change was made, it was found that the circuit had adequate stability.

4.11 Micromax Range Change. In Alpha II a change in the type of charge used in the ion source made it necessary to operate the charge heater at a temperature lower than the normal range of the Micromax during the start of each run. To control the temperature of the charge heaters during the start-up period, it was necessary to lower the range of the Micromax to include the operating temperature. A fixed resistor inserted in series with the primary of the Thermohm transformer met the requirements.

4.12 Beta Remote Temperature Control. In Beta the heater cubicle and the high-voltage cubicle were located in separate areas and required an operator for each. The need for an operator at the heater cubicle could be eliminated if the temperature controller and indicator could be operated from the high-voltage cubicle. Although space limitations and other factors prevented the moving of this equipment to the high-voltage-cubicle location, remote control of the temperature recorder from the high-voltage cubicle was feasible.

Remote control was accomplished by providing a 20-point switch with the proper resistance value in the temperature-controller bridge circuit to change the temperature settings in increments of 10°C and a 10-point switch for fine adjustment in 1°C steps. A band-change switch provided control in three ranges, 200 to 400°C, the normal range of 350 to 550°C, and an upper range of 400 to 600°C. A meter at the remote-control station indicated the deviation in temperature

within a range of ±20°C. Thus the high-voltage-cubicle operator was able to make temperature adjustments within the range of control and to read the temperature at the high-voltage-cubicle station. The addition of remote control to the Micromax bridge circuit is shown in detail in Fig. 14.15. The addition to the Bailey instrument is shown in Fig. 14.16. A direct result of the addition of remote control was a considerable reduction in heater-cubicle operating personnel.

5. HEATER-EQUIPMENT SERVICE REQUIREMENTS

5.1 Heater Load Requirements. In Alpha I the interfin heaters had a combined resistance of 2.2 ohms, and the transformer was rated single phase, 60 cycles, 4 kva, 460/100 to 70.5 volts in eight steps, and with 50 kv primary-to-secondary insulation. Assuming that the interfin-heater transformer was operated at maximum output voltage, it would then have been operated at 100 per cent of rating. This equipment was operated less than one month, and no failures were experienced with the transformers.

In Alpha II the interfin-heater transformers were operated with an average load of 2.0 amp at 460 volts, 0.92 kva. This transformer was rated 13.0 amp, 460 volts, 6 kva.

The Alpha I arc-chamber heaters had a combined resistance of 5.3 ohms. The transformer was rated single phase, 60 cycles, 4 kva, 460/100 to 50 volts in eight steps. With the heater transformer operated at maximum output voltage, the load was only 50 per cent of its rating. This transformer was operated for a short period of time before the arc-chamber heaters were paralleled with the charge heaters and the transformer was removed from service.

In Alpha II the arc-chamber-heater transformer was operated with an average of 2.5 amp at 250 volts, or 0.625 kva. The transformer was rated 9.5 amp, 420 volts, or 4.0 kva.

After the arc-chamber heaters had been paralleled with the charge heaters in Alpha I, the combined load resistance was 2.4 ohms. The charge-heater transformer was rated single phase, 60 cycles, 2.5 kva, 430/100 volts. The combined load of the arc-chamber heaters and the charge heaters was supplied by this transformer. Its load varied between 20 and 110 per cent of its rating.

In Alpha II the charge heaters were operated at an average current of 2.6 amp at 280 volts, or 0.728 kva. The charge-heater transformer was rated 4.24 amp, 450 volts, or 2 kva.

In Beta the charge-heater transformer was rated 2 kva, 415/100 to 70.5 volts in eight steps. The load consisted of two 70-volt 1,000-watt heaters connected in parallel. These transformers were overloaded when they were fully on. The overload lasted for the short period of

time necessary to bring the charge up to temperature and did not prove detrimental to the charge-heater transformer.

The saturable reactor used in conjunction with the Alpha I charge-heater equipment was rated 6 kva, 460 volts, and was operated at approximately 75 per cent of its rating. In Alpha II the saturable reactor was rated 6 kva, 460 volts alternating current, and was operated at 1.5 kva, 250 volts alternating current. In the Beta equipment the reactor was rated 4 kva, 460 volts alternating current, with its maximum load being below its nominal rating.

5.2 Heater Temperature Requirements. Alpha I used as a temperature indicator a Micromax having a range of from 0 to 500°C. The Reactrol had sufficient sensitivity and had adequate rating to supply the saturable reactors with the necessary d-c power over the range of the temperature indicator.

In Alpha II the Micromax had a range of from 350 to 550°C and with its Reactrol temperature-control system had adequate range for the operation of the process equipment.

In Beta the operating range of the controllers was from 350 to 550°C, but a greater range was required for satisfactory operation. This equipment was modified and with remote control provided three ranges of 250 to 400, 350 to 550, and 400 to 600°C.

The temperature of the charge was not dependent solely on the power supplied by the charge heaters because large amounts of heat were dissipated in the charge casting owing to the electron drain currents of other supplies associated with the source. This additional heating was known as "drain heating" and was detrimental in that it acted to prevent the temperature controller from maintaining the charge at a constant temperature. Drain heating occurred in the mass spectrograph owing to overheating of the ion source by excessive accell current particularly in the arc-chamber region, which reflected heat into the charge. Drain heating occasionally was of such a magnitude that even with the charge heater deenergized the charge temperature would be higher than desired. This condition could be corrected by reducing the accell voltage with a loss of production. It became necessary in Alpha I and Alpha II to establish a compromise operating condition by reducing the accell voltage until the temperature-control equipment could maintain a charge temperature at approximately the desired value. In Beta the condition was alleviated somewhat by heat shields and water-cooling pads designed and built into the process units. Some improvement could be made by changing the differential temperature between the arc-chamber heaters and the charge casting. Under drain-heating conditions the arc-chamber casting was operated

at a higher differential temperature with respect to the charge casting, this being accomplished by adjusting the taps on the two transformers.

More recently the arc-chamber heaters have themselves been a source of heat feedback to the charge, and in many instances operation could be maintained without arc-chamber heaters once stable operating conditions had been established.

5.3 Heater-equipment Failures. Very few failures were experienced with the heater-control equipment, and its service record was satisfactory. A great deal of trouble was experienced with Reactrol temperature-control equipment. It was very difficult to maintain accurate temperature control. The troubles experienced are discussed in detail in Chap. 5. The transformer used to supply the heaters in Alpha I did not have an excessive failure rate, and no transformer failures were experienced in Alpha II. In Beta a few of these transformers failed owing to high-voltage flashovers. No failures were experienced with the saturable reactors associated with these transformers.

The Micromax temperature controller used in Alpha I and Alpha II required only normal servicing. In Beta, trouble was experienced with the Micromax because of the sticking and burning out of the motor. This burning out occurred when the grease in the bearing became dry and hard. The trouble was eliminated by changing the grease periodically.

A large number of slide-wires in the bridge circuit of the Beta Micromax burned out as a result of short circuits that occurred between the heater leads and Thermohm leads within a common five-conductor cable-connecting jumper. A rigid inspection and repair program of this flexible jumper was instituted.

In the Beta Bailey Pyrotron a large number of rectifier tubes proved defective because of cathode-plate short circuits. These defective tubes resulted in a large number of rectifier-transformer failures. Tube failures were also the greatest source of trouble in the case of the Reactrol used with the various temperature controllers. The rate of failure of the 6SN7 tubes used in the Reactrol was considerably above normal when the Reactrol was used with the Bailey controllers.

5.4 Maintenance Equipment and Procedures. The operating buildings were furnished with what were known as "dummy loads" to facilitate the servicing of the channel auxiliary electrical equipment. These dummy loads consisted essentially of resistors or a bank of resistors which when connected to the supply line offered to that supply a load equivalent to the interfin heater, the arc-chamber heater, the charge heater, the filament, and the arc. The Alpha I dummy load also in-

cluded a battery-potentiometer-millivoltmeter combination that could simulate the output of the temperature-measuring thermocouple. In addition the Alpha II and Beta dummy loads included calibrated rheostats to simulate the Thermohm resistance at various temperature values.

Each of these dummy loads was enclosed in a metal cubicle and mounted on wheels for ready movement from one channel to another. The cubicle was forced-air cooled.

The process buildings were furnished with dummy supplies for checking the mass-spectrograph equipment after servicing and prior to installation. These dummy supplies provided power to the various heater circuits and the necessary metering equipment for checking the thermocouple and Thermohm circuits. The physical construction of the dummy supplies was similar to that of the dummy loads.

In addition to the dummy supplies, tank-heater supplies were used in the Alpha II plant. When channel-equipment failures occurred which required extended repair time, near-operating temperatures were maintained in the mass spectrograph during this time. The independent tank-heater supplies were connected directly to the heater circuits, and the normal channel-heater supplies were deenergized, permitting servicing of the cubicle equipment. A 60-cycle single-phase 6-kva 460-volt transformer with two secondary windings was utilized to supply the heaters. The first secondary winding was rated 2 kva, 60 volts, and the second was rated 4 kva, 60 volts. The secondary had taps at 50, 40, and 30 volts; and on the 30-volt tap 300°C was maintained as an optimum temperature during the repair period.

To ensure accurate calibration of the temperature controller and indicator in Alpha II and Beta, a dummy Thermohm of manganin wire was used. The resistance of this dummy Thermohm was 22.275 ohms, which was equivalent to the resistance of the standard Thermohm at 460°C. With this dummy Thermohm connected to the temperature-control circuit, the temperature-control pointer was set at 460°C, and any deviation of the temperature indicator from this value was corrected by an adjustment of the rheostat included in the bridge circuit. The adjustment of the controls for the Reactrol was far more complicated. This adjustment depended on the effect of drain heating, the desired operating temperatures, and the condition of the Thermohm installation.

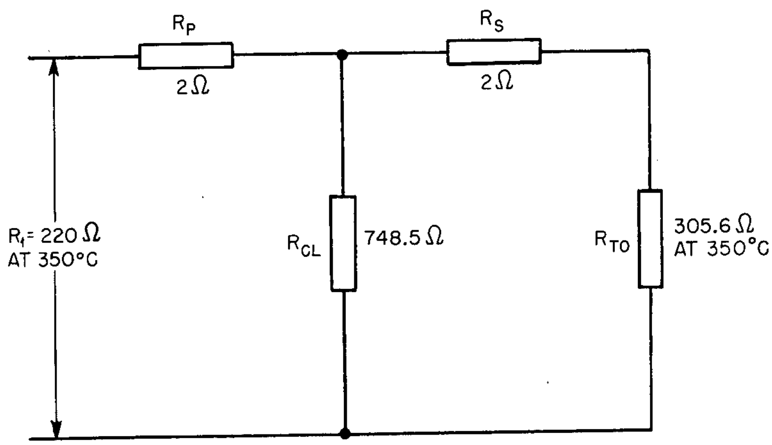


Fig. 14.1—Equivalent circuit of the Thermohm transformer and Thermohm used in Alpha II and Beta.

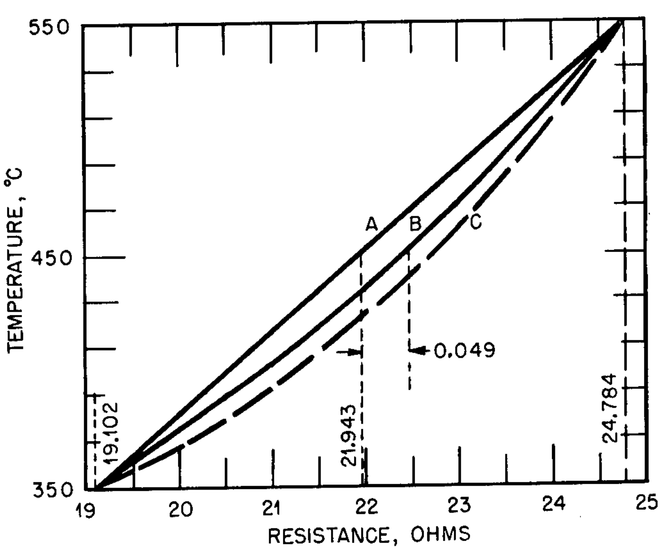


Fig. 14.2—Resistance-temperature characteristic of Thermohm used in Alpha II and Beta. Nonlinearity exaggerated 10 times. Curve A, linear. Curve B, Thermohm. Curve C, Thermohm and transformer combination.

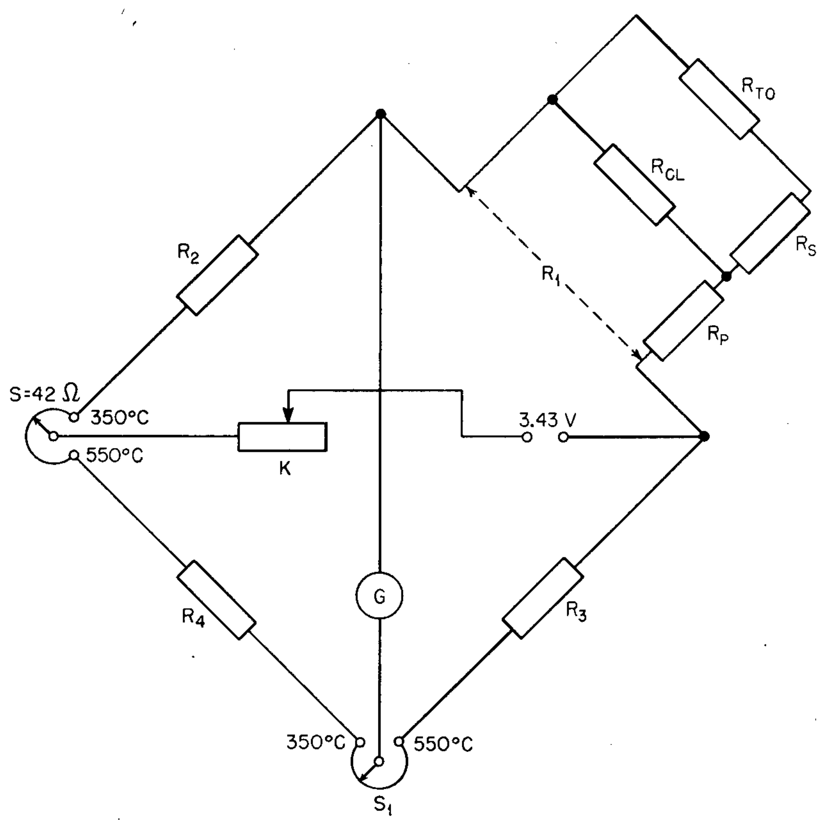


Fig. 14.3—Equivalent bridge circuit of Micromax temperature controller used in Alpha II and Beta.

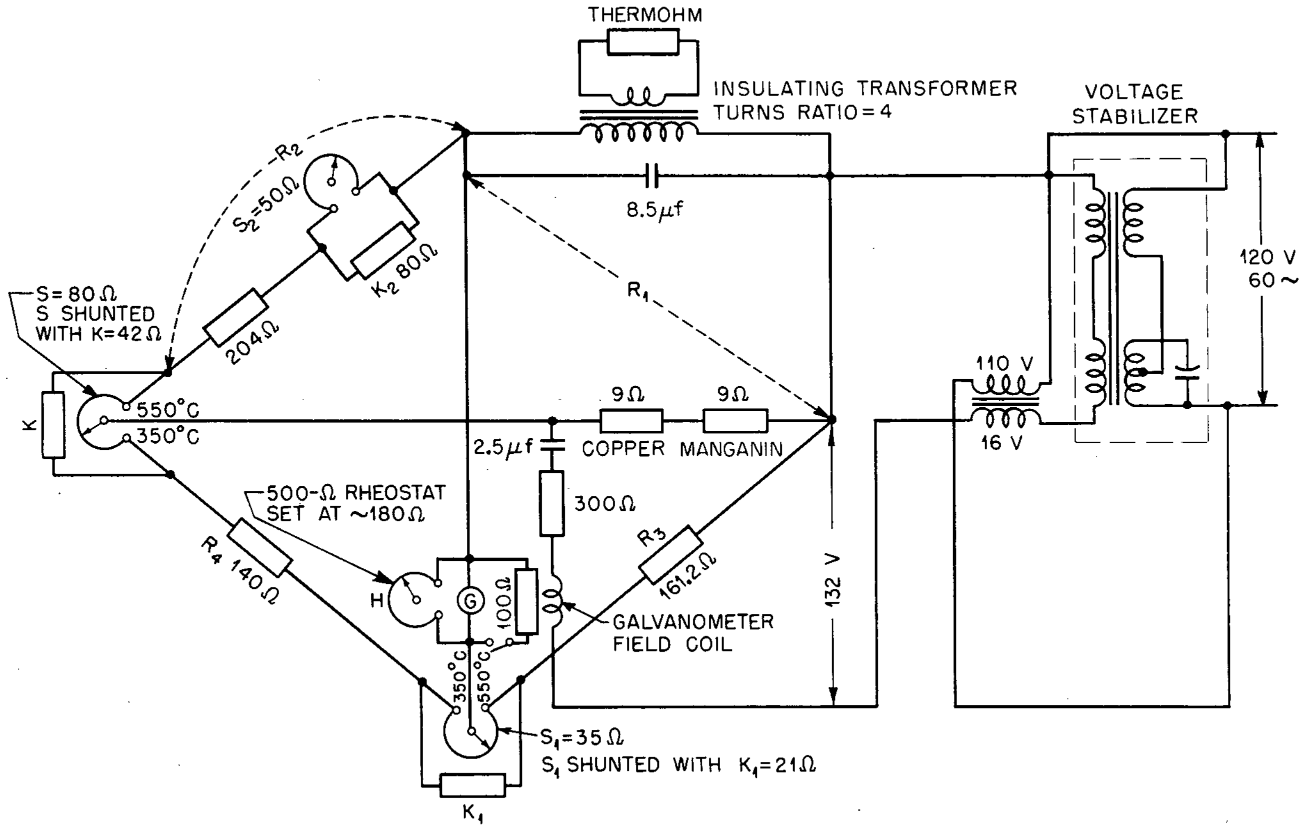


Fig. 14.4—Schematic diagram of Alpha II and Beta Micromax.

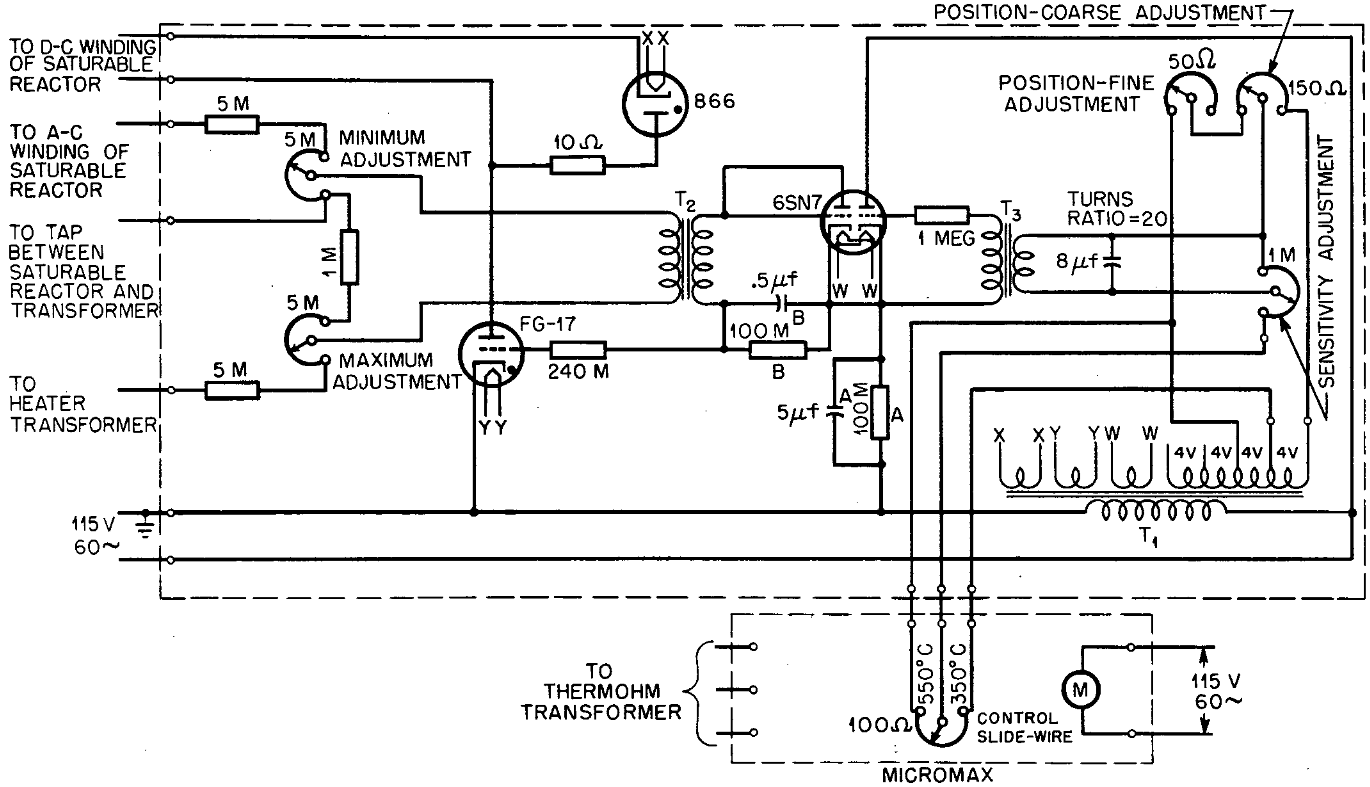


Fig. 14.5 — Schematic diagram of General Electric Reactrol control panel.

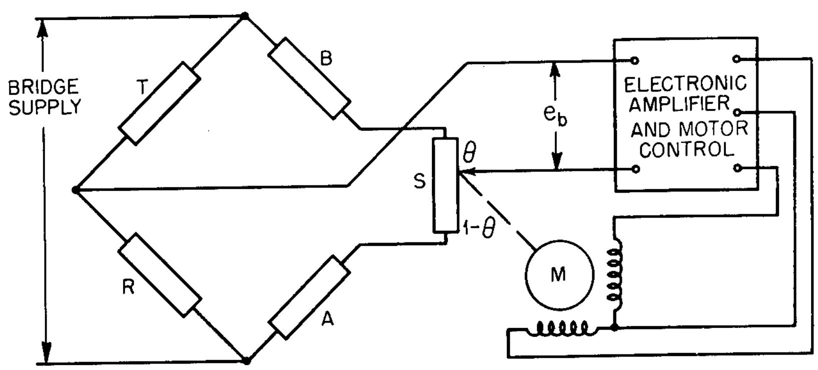


Fig. 14.6—Simplified schematic diagram of the Bailey Pyrotron showing modified Wheatstone bridge. T, temperature-sensitive resistance. A, B, and R, fixed resistance. M, slide-wire drive motor. S, slide-wire. θ, position of slide-wire contact.

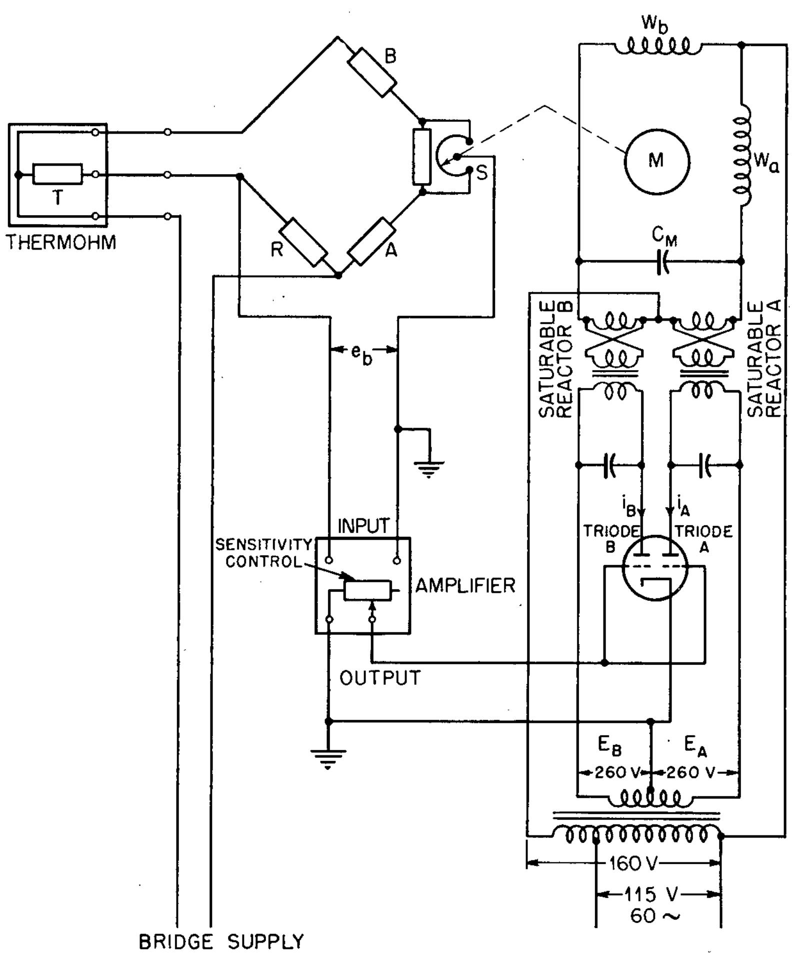


Fig. 14.7—Schematic diagram of the Bailey Pyrotron.

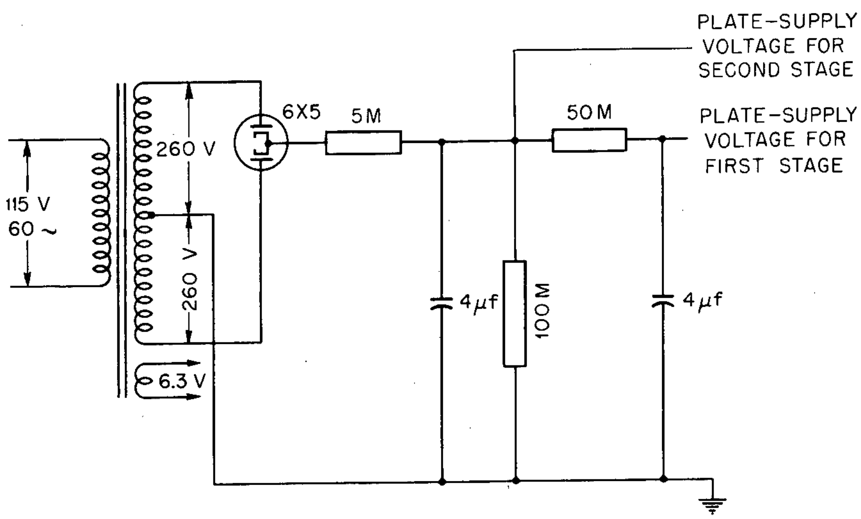


Fig. 14.8—Schematic diagram of the Bailey Pyrotron d-c power-supply unit.

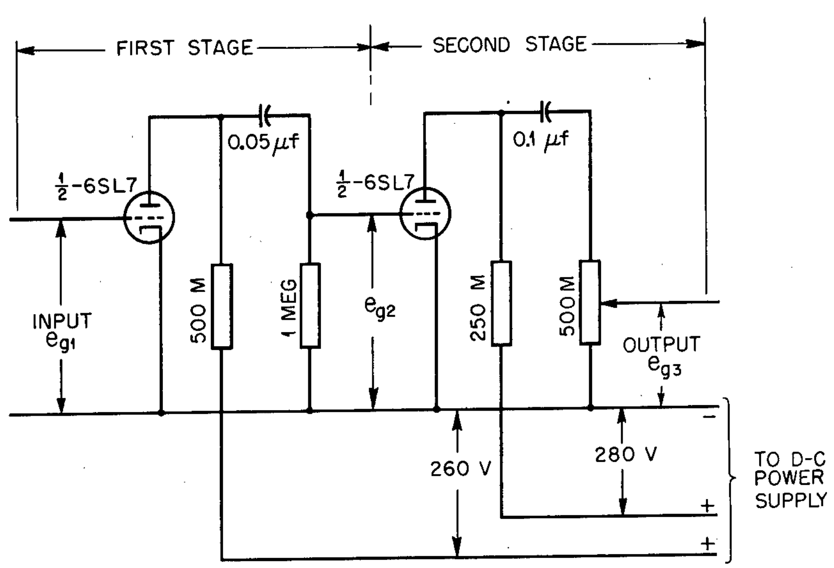


Fig. 14.9—Schematic diagram of the Bailey Pyrotron voltage amplifier.

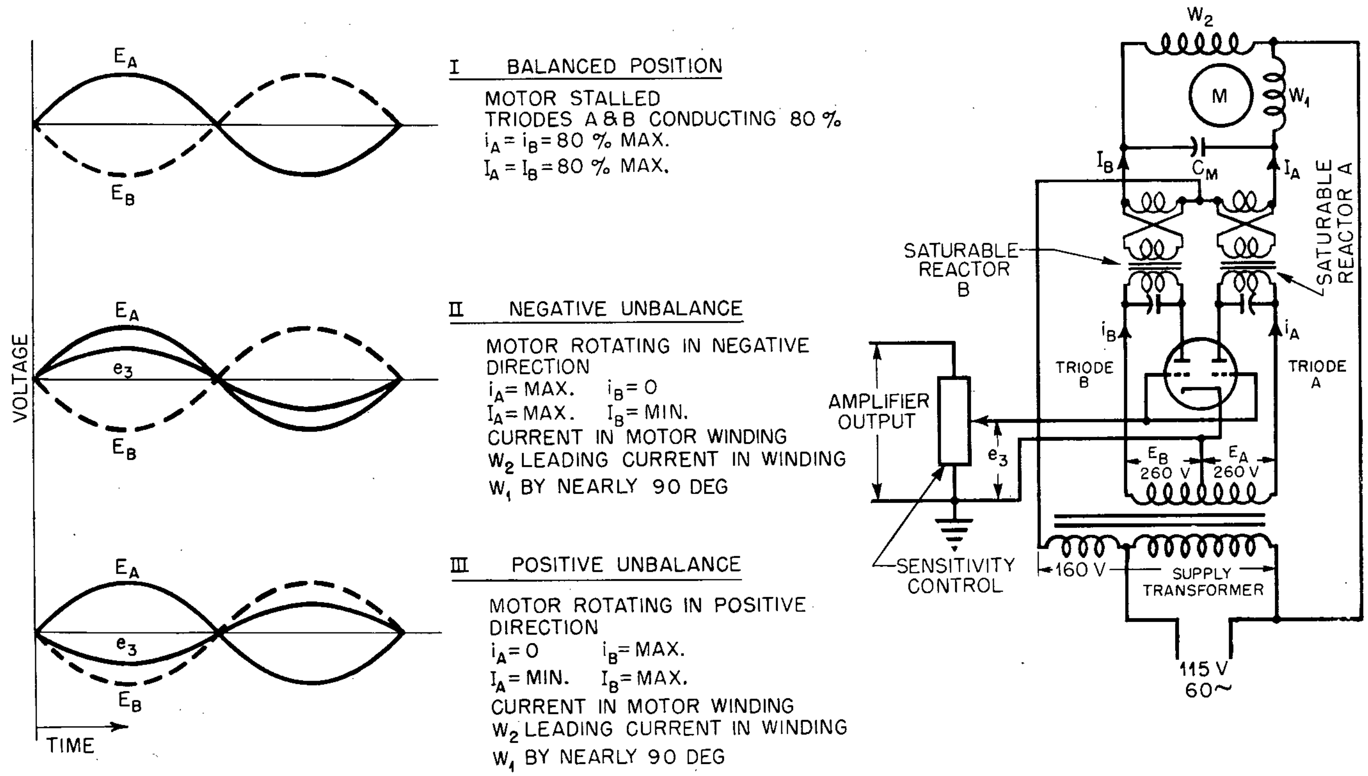


Fig. 14.10—Schematic diagram of the Bailey Pyrotron motor control.

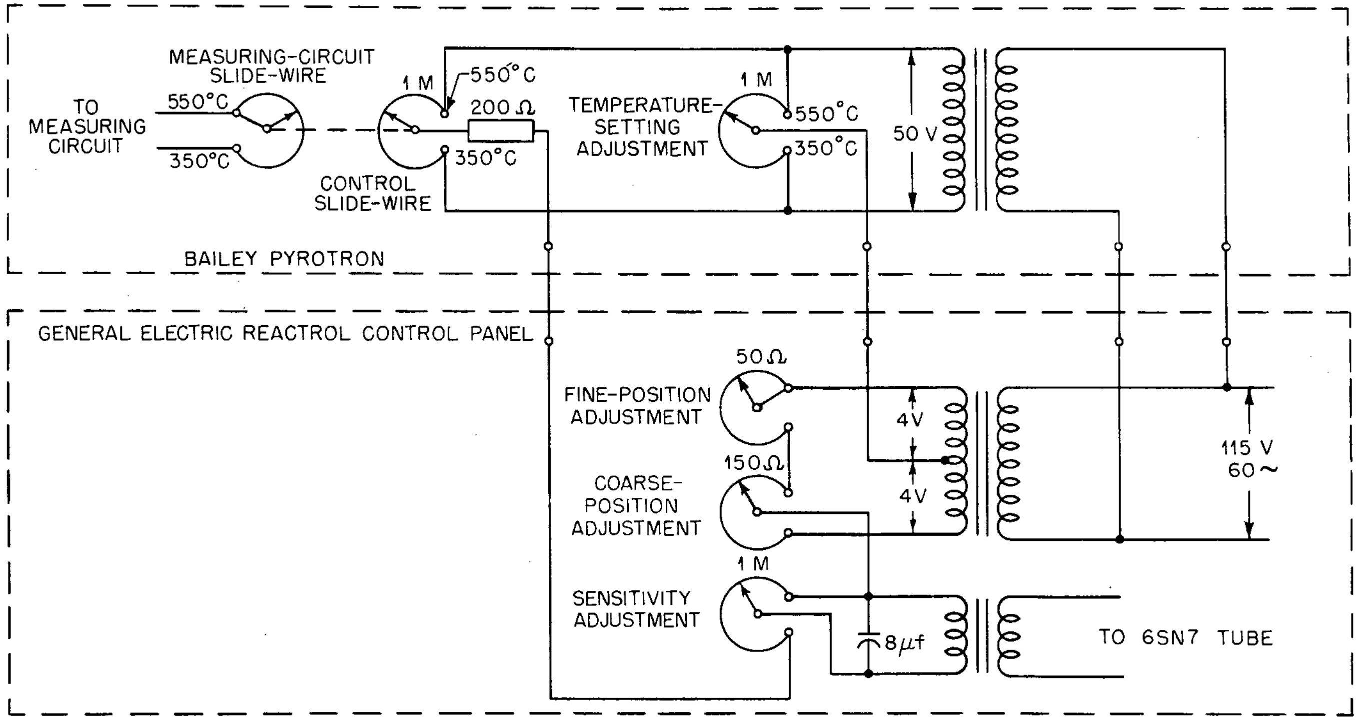


Fig. 14.11—Schematic diagram showing the relation between Bailey Pyrotron and General Electric Reactrol heater-control panel.

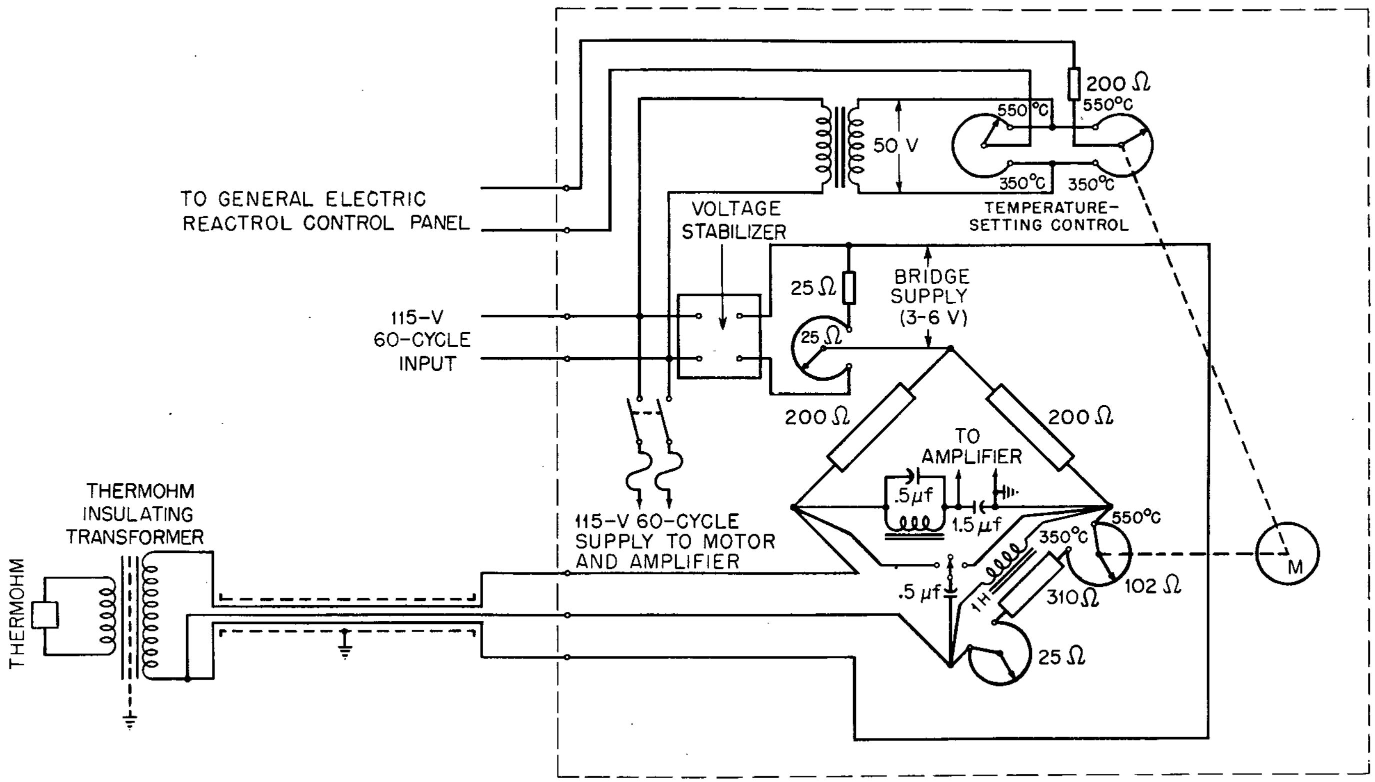


Fig. 14.12 — Simplified wiring diagram of Bailey Pyrotron measuring and controlling circuits.

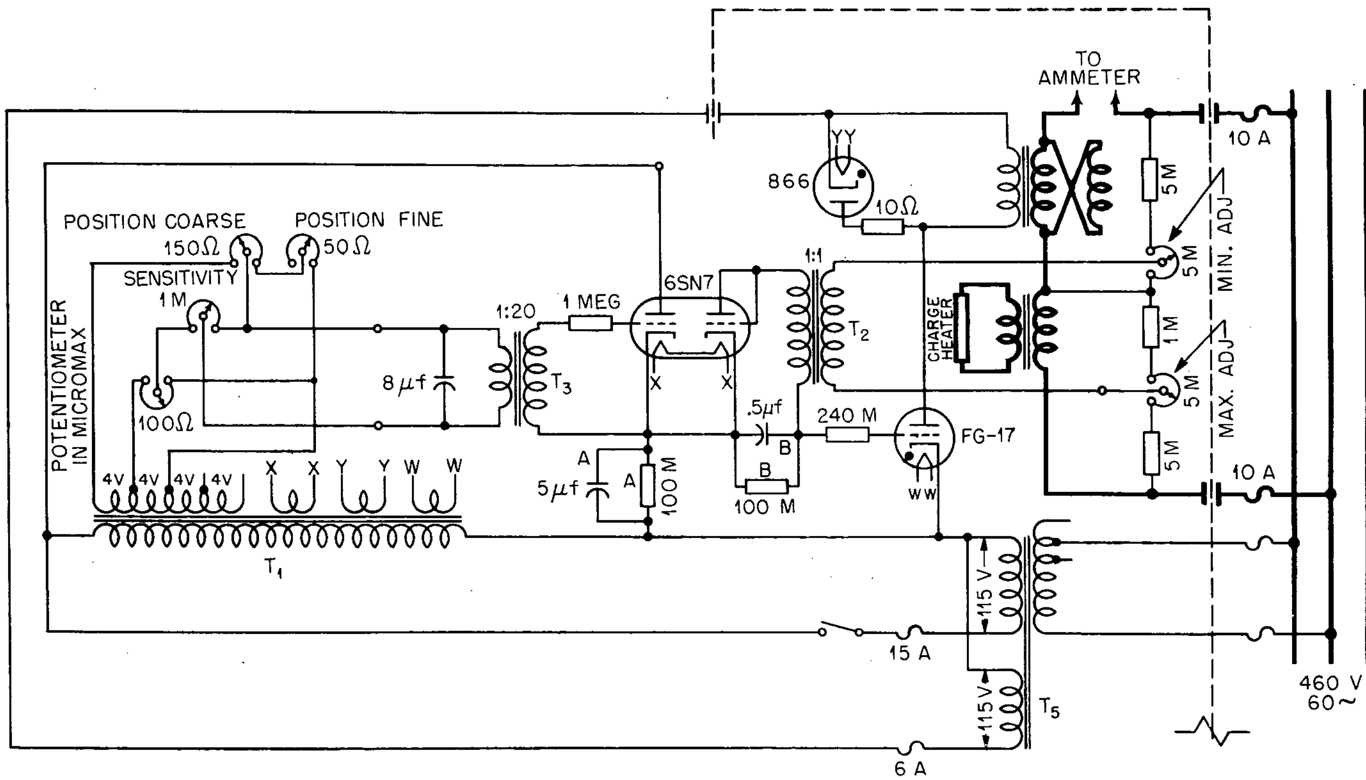


Fig. 14.13—Schematic diagram of General Electric Reactrol control.

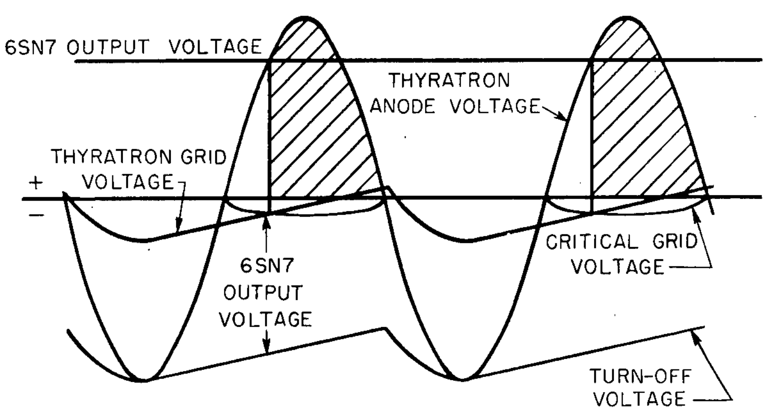


Fig. 14.14—Typical thyratron control voltages in the General Electric Reactrol heater control.

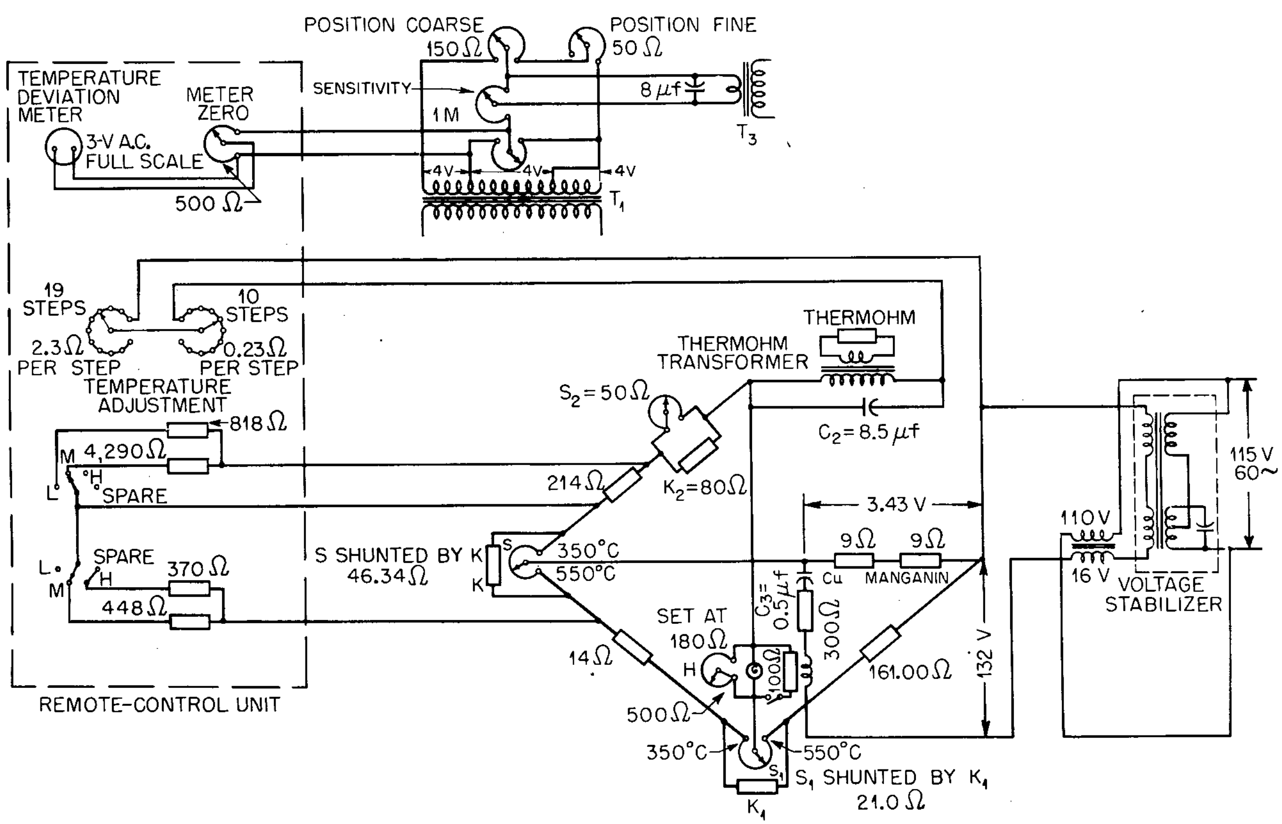


Fig. 14.15—Schematic diagram of the Micromax remote control.

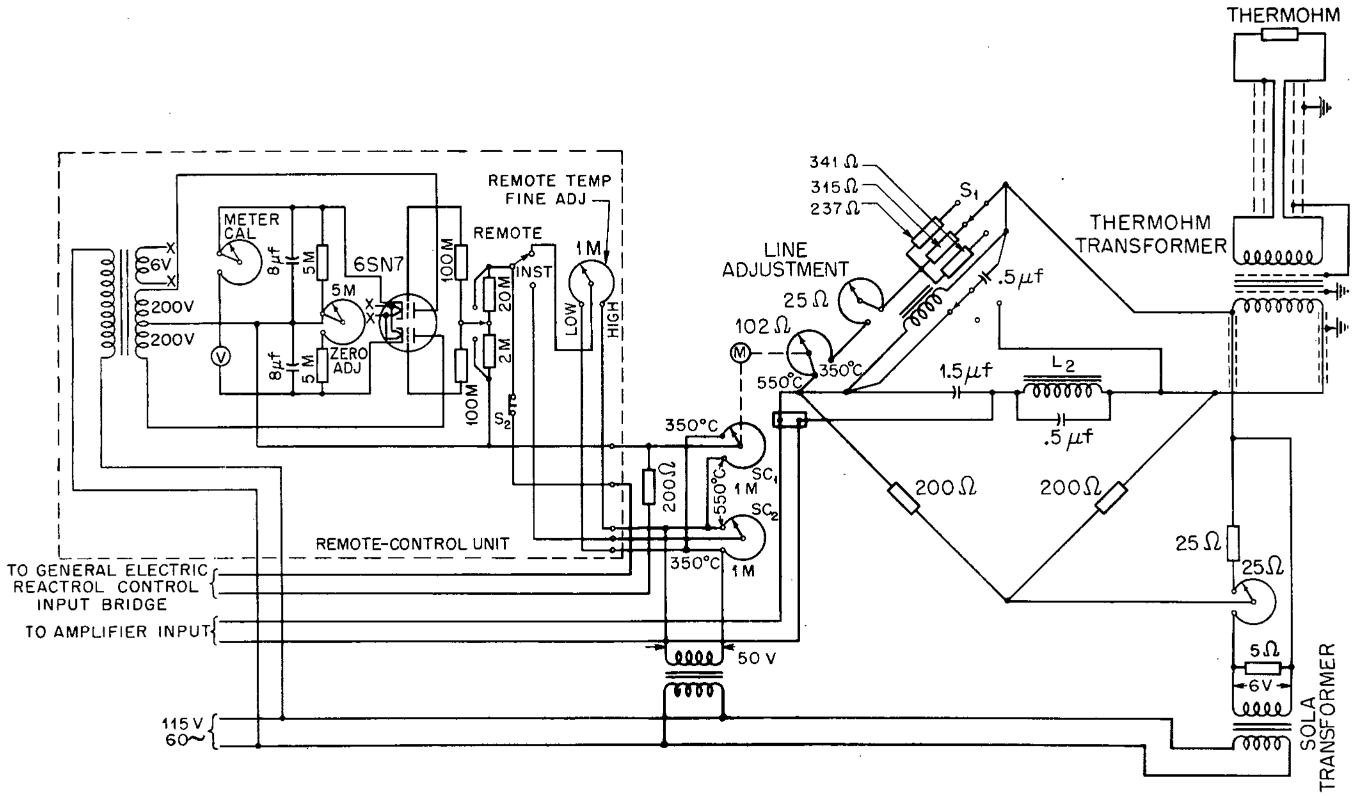


Fig. 14.16—Schematic diagram of the Bailey Pyrotron remote control.

Chapter 15

EXPERIMENTAL AND THEORETICAL STUDIES

1. TEMPERATURE-CONTROLLER SURGE FILTER

In Alpha II the Micromax indicated sharp temperature deviations from the desired value. These deviations were on the high-temperature side and occurred at a rate of approximately twenty per hour. To determine the cause of such deviations, tests were conducted under normal operating conditions, a zero temperature-coefficient resistor mounted externally to the tank being substituted for the Thermohm. When the resistor replaced the Thermohm, no temperature deviations were indicated. To simulate the Thermohm in vacuum, a small flashlight bulb was substituted for the externally mounted resistor, and the Micromax again indicated the same sharp temperature deviations that had appeared when the Thermohm was used. These two tests seemed to indicate that high-frequency transient currents were heating the Thermohm.

A low-pass π-type filter connected between the Thermohm and the Thermohm insulating transformer did not improve conditions. Study of the circuit suggested that the Thermohm and the first capacitor of the filter probably formed a resonant circuit for the high-frequency current. This capacitor was removed, leaving the Thermohm in series with the choke, and the combination was shunted by a capacitor. This type of filter eliminated the temperature deviation without disturbing the reactance balance of the bridge.

2. TEMPERATURE-CONTROL STUDY

Because considerable trouble was experienced in maintaining constant charge temperature, the temperature indicator and control system were studied extensively.

Essentially this system was a closed loop controller, which tended to lock in at the set operating point so that any disturbance produced

a reaction in a direction to reduce the original disturbance. The important factors affecting control are stated in the following paragraphs.

2.1 Thermal Capacity. In a system being controlled to maintain a constant temperature or a slowly increasing temperature, thermal capacity should be large compared to the rate at which heat may be added to or removed from the system. This large thermal capacity acts as a large flywheel in smoothing out the energy impulses to the system and the releases from it. For this reason the larger Alpha heater units were easier to control than the smaller Beta units.

2.2 Heat-transfer Lag. A retardation of response caused by the temperature gradient and thermal resistance between the unit heaters and the temperature-measuring element was disadvantageous since a slow initial response resulted in slow corrective action by the temperature controller. The transfer lag in the Beta unit was from 1 to 2 min but sometimes was as long as 4 min.

2.3 Controller Dead Zone. The controller dead zone, the region within which the controller had no response or control, was a small fraction of a degree, which was negligible for a properly operating system but was increased by excessive friction or mechanical backlash in the moving parts of the temperature indicator or by improper reactive balance in the bridge-circuit Bailey recorder. Improper reactive balance left a 90-deg component of voltage across the bridge output, which could not be automatically balanced since the system adjusted only the resistive component. This 90-deg component resulted in either overloading the amplifier or saturating the reactors controlling the motor of the Bailey recorder.

The heater-control system was a proportional type, i.e., the change of heater temperature was determined by the change in the thermocouple or Thermohm temperature and was proportional to it. The casting temperature plotted against the heater current is essentially a straight line. The input voltage to the Reactrol control plotted against Thermohm temperature is a straight line. Heater current can be plotted against Reactrol input voltage, and the resulting curve will have the same shape as the curve does when Thermohm temperature is plotted against casting temperature. The sensitivity of the control system can then be defined as the amperes of heater-current change per degree centigrade temperature change. In any closed-loop proportional controller there is a sensitivity above which oscillations will start and build up to the saturation point of the amplifier. Above this point the system will oscillate with a constant-amplitude sine wave. Below this point any oscillation that starts will be effectively

damped out. The ultimate sensitivity at which oscillations occur is determined by the thermal capacity and transfer lag of the system. The frequency of oscillation is determined primarily by the transfer lag. For a system with a fixed thermal capacity and a fixed transfer lag, there is an ultimate sensitivity that will produce oscillation. Usually a sensitivity of approximately one-half this value will properly damp out system disturbances. The Beta units in use in October 1945 were found to have an ultimate sensitivity of 0.2 to 0.3 primary ampere per degree of temperature change. This value is given in terms of primary current as measured to the heater transformers since this was the customary measure used in the CEW-TEC plant.

Drain heating affected the sensitivity of the temperature-control system. The sensitivity figures given were for a condition of no drain heating where a 0.1-amp change in heater current would produce a certain temperature change and a 0.2-amp change would produce twice as large a temperature change.

When operating conditions were such that drain heating occurred, a 0.1-amp change would produce a greater temperature change than would occur when no drain heating existed. The result of drain heating would give an effective increase in sensitivity or even a nonlinear relation between heater current and casting temperature. In extreme cases this increase in sensitivity was sufficient to cause more of an increase of temperature by drain heating than the control could account for by decreasing the heater current. This resulted in a runaway condition where the automatic control reduced the heater current to a minimum and had no further control until the temperature was decreased by other operating techniques.

From the stability standpoint alone, a low sensitivity setting was desirable since it reduced the tendency of the system to oscillate. The drawback to using a sensitivity setting a great deal lower than the ultimate value was that with proportional response only one value of heater current for which the indicated temperature agreed with the selected temperature could be maintained automatically. Automatic control is based on deviation, and, before a controller can act, a deviation, no matter how small, must occur. Any change such as the amount of drain heating or a change of the operating temperature required a new value of heater current that the controller could not provide except by having the indicated temperature differ from the set temperature. The differences between set temperature and indicating temperature were known as "lead" and "lag," lead being the condition existing when the indicated temperature was higher than the set temperature.

The correct adjustment of proportional-response sensitivity involved balancing oscillation tendency and lead. The degree of lead varied inversely with the sensitivity. To provide reasonable margin against oscillation, a sensitivity higher than one-half the ultimate value could not be used, even though it would have been desirable from the standpoint of lead alone. In plant operation a sensitivity of one-half the ultimate value, 0.10 to 0.15 amp per degree centigrade, was used with little trouble due to oscillation. Checks at the time the tests were made (October 1945) showed that the average primary charge-heater current varied about 2 amp from beginning to end of the run. For example, a typical unit which required 2 amp at 360°C required 4 amp at 590°C. Owing to cooling differences the variation between units spread from 1.6 amp minimum at 360°C to 4.8 amp maximum at 590°C. At a sensitivity of 0.1 amp per degree centigrade this meant that a temperature deviation of 20°C was necessary to cause a 2-amp heater-current change. With the hold current manually set to the mid-range value of 3 amp, the lead at the start-up temperature of 360°C would be 10°C to hold the current at 2 amp. As the temperature settings were increased during the run, the lead would decrease to zero by the time the temperature had reached approximately 475°C, and the lag would increase as the temperature was further increased with a maximum lag of 10°C at approximately 590°C.

The result was a lead and lag of approximately 7 to 10°C without manual resetting; but with proper selection of the hold current the center section or longest part of the run would have only 2°C deviation. The hold current was defined as that current required to hold the temperature at a steady value. Because of variations in cooling between units, drain heating, etc., there was no single value of hold current for all units for a given temperature.

Best operation resulted when the over-all sensitivity remained the same at all temperatures. Neglecting drain heating, a variable factor, this constant-sensitivity characteristic for the Reactrol control would have been a straight-line relation between heater current and input voltage to the Reactrol. Even with drain heating this straight-line relation was desirable since over a narrow temperature range the sensitivity curve could be considered a straight line. The effect of drain heating was to make this line steeper, which meant higher sensitivity. The effect seemed to be similar at low and high temperatures.

At one time it was thought desirable that the Reactrol reduce the heater current extremely rapidly when drain heating caused a rise in temperature. From the heating standpoint alone this was desirable. If the control could have been adjusted to operate at maximum usable

sensitivity at all temperatures selected and with a steep cutoff characteristic for conditions of lead, this idea could have been used. Actually this double characteristic was not present in the heater control. Control effect was measured as primary charge-heater current vs. temperature displacement between the setting and the indicating pointers because there was a linear relation between input signal and pointer displacement. The group of curves shown in Fig. 15.1 shows the effect of varying the minimum control of the Reactrol circuit. These curves are numbered to agree with the setting of the minimum control. Curve 6 is typical of the Reactrol characteristics in use in October 1945. It was quite different from the desired straight-line characteristics proposed above and in operation gave results that were extremely unsatisfactory. The slope is steep at the low-current end. This was due to an effort to get a characteristic that decreased the heater current rapidly for a condition of temperature lead. It did not reduce the current as rapidly as the other straight-line curves shown. The result of such a characteristic was high sensitivity at low heater current, which caused oscillation in a majority of the units during start-up at the low end of the temperature range. Also some units with high drain heating and poor cooling operated at low current throughout the run with severe oscillation. At high current the sensitivity was very low. This would not cause oscillation but would cause severe temperature lag; the curve is headed toward 4.65-amp maximum, which is not reached until the lag is 30°C or more.

The curve shown in Fig. 15.2 indicates the cause of the nonlinearity of curve 6, Fig. 15.1. The curve shown in Fig. 15.2 is a graph of the output signal voltage of the first tube in the Reactrol vs. its grid voltage. The positive grid region of the tube characteristic is flat, and the negative region is steep. Curve 6, Fig. 15.1, is an expanded reproduction of Fig. 15.2 about the zero grid-voltage point. Different 6SN7 tubes showed widely different characteristics in the positive grid region but were uniform in the negative grid region for which they were designed. To get a straight-line relation between heater current and input signal, the straight line or negative grid-voltage portion of the curve must be used. This portion is steeper than the zero grid-voltage region, and the sensitivity is higher. As a result the sensitivity must be reduced elsewhere to prevent oscillation.

A sensitivity control had been provided on the Reactrol control panel. This was essentially a linear control between the output of the temperature indicator and the input to the Reactrol. The sensitivity control was marked from 1 to infinity, 1 being the most sensitive position and infinity being zero sensitivity.

To show that the sensitivity could be reduced by other controls besides the sensitivity control, data were compiled from which Figs. 15.1 and 15.3 were drawn. Figure 15.1 shows the effect of the minimum control on the Reactrol characteristic. For all the curves shown in Fig. 15.1 the maximum heater current was the same at 30°C or more temperature lag. Curve 6 was typical of the characteristic in use in October 1945. Curves 7 to 10 show the effect of moving the minimum control to the position indicated on the curves, leaving other conditions fixed. This control definitely changed the slope of the curves and affected sensitivity, but it could not be predicted from the dial numbers. The discontinuity of the curves between curves 6 and 7 was due to operation in the positive-voltage region of the 6SN7 tube grid voltage. When this transition region was avoided, the minimum control affected the sensitivity, with minimum sensitivity occurring at position 10 on the control dial. The minimum control affected the low-current section of the curves but did not determine the minimum current that depended on the saturable-reactor impedance at zero saturating current. The minimum current used for the curves shown was 0.25 amp or less.

The curves of Fig. 15.3 show the effects of varying the maximum control with the minimum control remaining on position 8 and with other conditions fixed. This control also definitely affected the steepness of the curves and did so in a degree that could not be predicted from the numbers on the maximum control dial. When the current was limited by means of the maximum control, the knee of the curve at the maximum end was not sharp, and the curves flattened out, indicating a reduction in sensitivity. It was desirable to limit the maximum current by the voltage-control tap on the charge-heater transformer and to use a setting of the maximum control that gave approximately a straight-line characteristic.

The maximum and minimum controls affect sensitivity to a degree that is unpredictable, but since they perform other intended functions, they definitely should not be used as sensitivity controls.

The sensitivity control determined that portion of the signal from the temperature indicator supplied to the input of the Reactrol. It was calibrated to give a definite known value for the relative sensitivity, i.e., 2 on the dial meant that the sensitivity was one-half that which was obtained at 1 on the dial.

In the proportional type of control, part of the signal was due to the temperature lead or lag and was supplied by the control circuit of the temperature indicator. When the sensitivity of the system was changed, it was necessary to reset the holding current manually to the same value at which it was set prior to the change in the sensitivity control.

Standard Reactrol settings were adopted that were believed to be the optimum for Beta operation. Figure 15.4 shows a typical curve for the Beta temperature-control system, using the settings that were adopted.

3. PROTECTIVE CIRCUIT FOR THE 6SN7 TUBE

In the Beta buildings in which the Bailey Pyrotron was used, the failure rate of the 6SN7 tube used in the Reactrol was exceptionally high owing to the large grid signal supplied to this tube by the temperature-control bridge. To limit the input to this tube to a safe value, a neon lamp that would conduct at approximately 20 volts was connected between the grid and cathode of the tube. This did not lower the grid voltage sufficiently to prevent failure of these tubes. A type 884 thyratron was substituted for the neon lamp, but this also failed to limit the grid signal to a safe value, and the experiment was abandoned, allowing the high rate of failure to continue.

4. DERIVATIVE CIRCUIT

In Beta, before it was proved that drain heating without the use of cooling pads was sufficient to cause temperature lead with no heater current flowing, an attempt was made to anticipate the rate of temperature rise and correct for it. A so-called "derivative circuit" was designed and installed in the Reactrol input circuit to adjust the input signal to lower the heater current as a function of the rate of rise of the indicated temperature. This circuit functioned satisfactorily but could not correct drain heating, the basic cause of the trouble. When it had been proved that the temperature lead was due to drain heating, water-cooling pads were installed in the unit to diminish heating of the charge by such drain currents, and the derivative circuit was removed from the temperature-control system.

5. ON-OFF TEMPERATURE CONTROL

Owing to the multiplicity of controls on the Reactrol with the attendant large maintenance problem, a simpler control was desirable. This resulted in an experimental installation in the Beta plant of an "on-off" temperature control. This system used a Powerstat for adjusting the hold current, and the switch cam on the Micromax was adjusted in such a manner that an auxiliary contactor would be operated by a change in temperature of approximately 0.5°C. This contactor short-circuited a resistor in series with the heater-power-supply circuit to cause an increase in the current to the charge heater. The

results of this experiment were favorable. It was abandoned, however, owing to the problem of drain heating and to the time and cost that would have been required to make such a change throughout the plant.

6. RELOCATION OF ALPHA I TEMPERATURE CONTROL

The Alpha I heater equipment was remotely located from the high-voltage cubicle, the major point of channel supervision. It was desirable to have the temperature indicator and controller located at the high-voltage cubicle under the supervision of the cubicle operator. To test the supposed advantages of such a system an experimental installation was made by moving the Micromax from the heater cubicle to the rear of the high-voltage cubicle.

This installation was not successful from a maintenance standpoint since adjustments of the Micromax and Reactrol system required two maintenance men, one located at the high-voltage cubicle and the second at the heater cubicle. From the standpoint of operation this installation did prove advantageous since the control operator no longer had to leave the high-voltage cubicle to go to the next floor each time a temperature change or indication was desired. As operating experience was gained, the number of trips made by the control operator was reduced, and the advantage gained offset the disadvantage accruing to the electrical maintenance personnel. This change was not made.

7. FLASH HEATERS

The original charge heaters were embedded in a metal casting used to support the charge bottle and the arc-chamber slits. The casting was heated by the charge heaters, and it in turn supplied heat to the charge. This type of charge heating resulted in an appreciable thermal lag through the casting with resultant temperature-control problems.

To overcome this thermal lag an experimental installation was made in which heaters were placed directly in the container. A thermocouple was also placed in the charge for direct measure and control of the charge temperature. The heaters utilized corresponded in ohmic value to those used in the castings of the Alpha I equipment and offered an equivalent load to the heater equipment.

Satisfactory operation was obtained when this heater equipment was used in the Alpha I plant, but a plant change could not be justified. Similar installations were also tested in the Beta channel but were also abandoned.

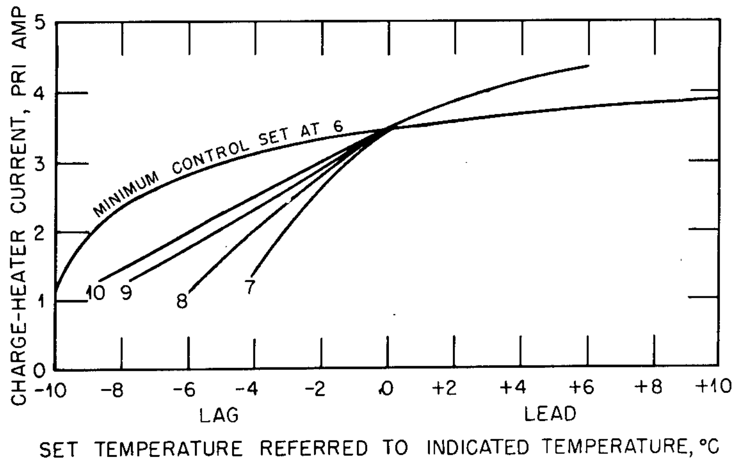


Fig. 15.1—Minimum control effect on sensitivity of General Electric Reactrol heater control. All curves reach a maximum of 4.65 amp (primary). Maximum control set at 7.

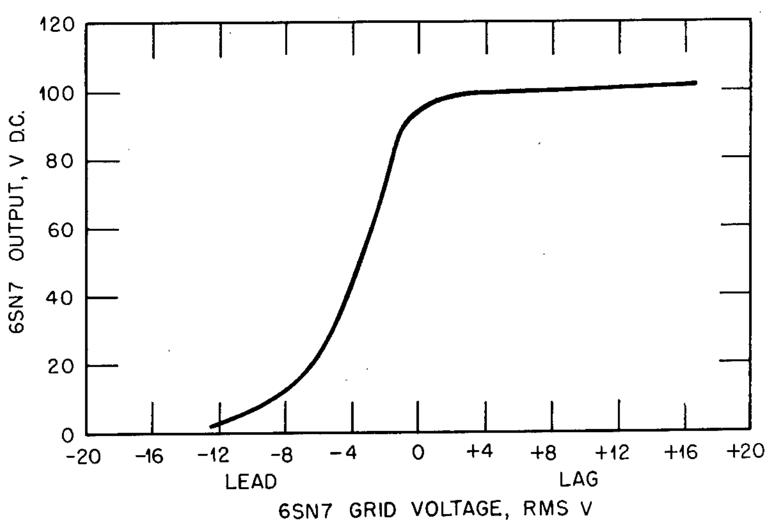


Fig. 15.2—General Electric Reactrol heater-control 6SN7-tube output voltage vs. grid voltage. Grid voltage is positive when in phase with plate voltage.

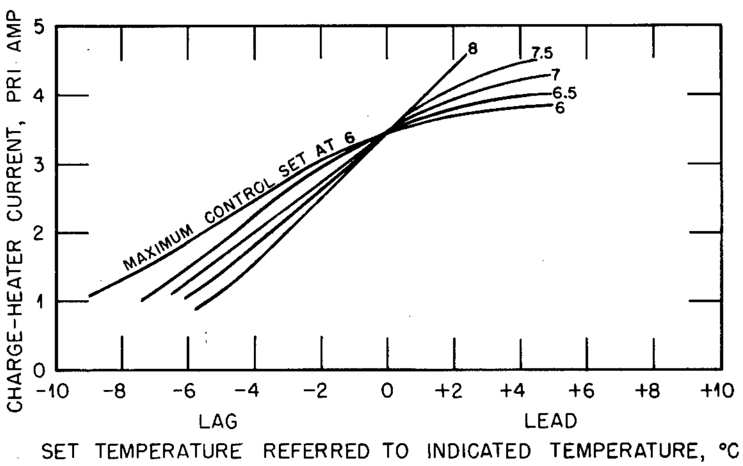


Fig. 15.3—Maximum control effect on sensitivity of General Electric Reactrol heater control. Minimum control set at 8.

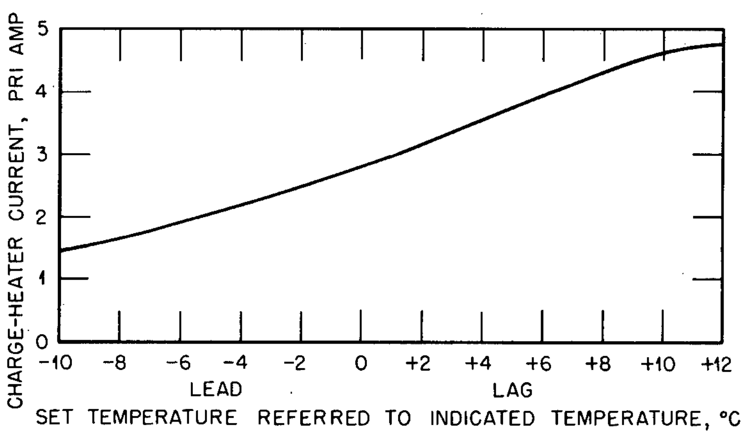


Fig. 15.4—Typical control characteristic of the General Electric Reactrol system. Maximum control set at 7.5. Minimum control set at 9.

Chapter 16

MISCELLANEOUS MOTOR CONTROLS

Control of the flow of vapor into the arc chamber was originally accomplished entirely through control of the temperature of the charge. Early in the history of operations the difficulties encountered with temperature control because of lack of experience made it desirable to have an auxiliary control that would have immediate response. A motor-driven vapor valve was introduced. As experience increased in servicing and operating temperature-control equipment and in the operation of the mass spectrograph itself, the need for the dual control was diminished, and vapor valves were eliminated.

The original outlet slits from the arc chamber were heavy and accumulated a deposit of sublimated charge. A hand-operated slit cleaner was provided, which was used at frequent intervals to keep the slits scraped clean. A later design was motor driven. The development of thin carbon slits that did not accumulate sublimate eliminated the use of the slit cleaner altogether.

1. VAPOR-VALVE ELECTRICAL SYSTEM

The vapor valve installed in the Alpha II mass spectrograph was operated by a reversing d-c motor whose armature was located directly in the magnetic field of the mass spectrograph. The armature of this motor was supplied by a copper oxide rectifier. This vapor-valve motor operated at decell potential with respect to ground, and the associated power-supply transformer was required to have insulation for operation in a 39-kv d-c circuit.

The d-c power-supply unit for each channel was designed to furnish power to two separate motors. This power supply was a complete assembly consisting of a transformer unit and a rectifier panel. In the first Alpha II building the slit-cleaner power supply (see Chap. 5, Sec. 6) was included in this assembly. In later Alpha II buildings the slit-cleaner supplies were not installed. The combined power-supply

assembly, as installed in the first Alpha II building, is shown in Fig. 16.1. Figure 16.2 is a view of the transformer removed from its tank.

The original transformer unit consisted of six single-phase transformers assembled in one oil-filled tank. Four of these transformers were assembled as a unit, having a common core-clamping structure. These four transformers were used as the vapor-valve supply and were each rated 60 cycles, single phase, 105 va, 115/63.1/50.8/38.2/26.0 volts. The two remaining transformers included in this assembly were used to supply the slit cleaner.

Each of the vapor-valve-supply transformers was connected to a copper oxide full-wave bridge rectifier. Each rectifier was capable of delivering 15 amp direct current continuously at 40, 30, 20, or 10 volts, depending on the transformer tap selected.

The secondary connections for these transformers were brought out through high-voltage bushings mounted on the transformer-case cover to the rectifier panel that was contained in an enclosure on the upper end of these insulators.

On the rectifier panel were the necessary copper oxide rectifiers and reversing relays used to connect the output of these rectifiers to the supply line of the vapor-valve motors. Also on the rectifier panel were the necessary capacitors to furnish surge protection for the copper oxide rectifiers.

Overload protection was provided in the primary of the power-supply transformer by a General Electric type CR-2824-41C thermal-overload relay utilizing a heater element rated 0.36 to 0.40 amp. The necessary control circuits were in the high-voltage cubicle so that the control operator could energize the power supply and control the direction of rotation of the vapor-valve motor.

2. VAPOR-VALVE-CIRCUIT CHANGES

After the Alpha II plant had been in operation for approximately one year, experience indicated that troubles associated with the vapor valve more than offset any advantages gained from its use, and the valves were removed from the mass spectrograph. The d-c power supplies for these vapor valves were then disconnected from the high-voltage decell line.

3. SERVICE CONDITIONS FOR VAPOR-VALVE SUPPLY

The vapor-valve-supply transformers were rated 115 va, 115/63.1/50.8/38.2/26.0 volts, and were operated with 115 volts on the primary. The secondary taps were set to give 50.8 volts. The operating primary load current was 0.35 amp, which resulted in 40.3 va. The rec-

tifiers, rated to deliver 1.5 amp at 40, 30, 20, 10 volts direct current, were operated at 1.3 amp at 30 volts direct current. All the equipment was operated well within its nominal rating.

4. SERVICE RECORD OF VAPOR-VALVE EQUIPMENT

The electrical supplies used to operate the vapor valves required very little electrical servicing. The major portion of the trouble experienced with this equipment was due to troubles in the mass spectrograph. Stuck vapor valves caused the thermal overload cutouts of the supply to operate. These overload cutouts were arranged to reset automatically, but a large number would not reset after having been tripped. This required a large amount of electrical servicing time, since such units had to be reset manually by the electrical maintenance personnel. Failure of the vapor valves to operate further complicated the problem since it was necessary for the electricians to determine whether or not the vapor valve had stuck or whether some portion of the vapor-valve electrical equipment had failed.

5. VAPOR-VALVE EXPERIMENTAL AND THEORETICAL STUDIES

5.1 Indication of Stuck Valve. In most cases vapor valves did not bind mechanically but failed to operate owing to the failure of the limit switches on the drive motor. Since the failure of these valves occurred quite frequently, it was necessary to have a way of determining whether the valves had stuck mechanically or whether the failure was due to some electrical cause. The operation of the valve was checked by placing a voltmeter across the thermal element of the overload protective device and observing the voltages at this point as the drive motor was operated in a direction to open the valve. If the valves were operating properly, this voltage would drop to zero when the limit switch had opened, indicating that the motor had reached the full-open position.

5.2 Thermal Vapor Valve. Experimental installations of a thermal vapor valve were made in Alpha I. These valves were opened and closed by the thermal expansion of an electrically heated metallic control strip. Power was supplied to the heaters of these valves from the high-voltage-cubicle control power circuit through a Variac position control. Electrically this valve operated satisfactorily, but mechanically it did not give a sufficient improvement in operation to warrant installation.

5.3 Magnetic Vapor Valve. Owing to the difficulties experienced with the original vapor valve installed in Alpha II, a new magnetic valve was designed and tested. These valves were controlled by the

interaction of the magnetic field with the field of two coils that were mechanically coupled to the valve. These coils were placed at right angles to each other and were wired so that the current to each could be varied, thus changing the angle of the resultant magnetic field. The resultant field produced by the two coils would tend to align with the field of the mass spectrograph and change the mechanical orientation of these coils and the valve. Tests of this particular valve were not satisfactory, and a more simple and compact control was designed.

The next design consisted of a single coil attached to a magnetic bar at right angles to the coil. The combination was mounted on the vapor valve so that when the magnetic bar was in line with the field of the mass spectrograph the valve would be open. To close the valve the field of the coil was increased until the resultant force between this field and that of the mass spectrograph was greater than the force exerted on the magnetic rod, thus causing the valve to rotate and close.

For both magnetic valves, power was supplied by the standard vapor-valve d-c power-supply unit. These designs were tested in an attempt to eliminate the reversible d-c motor with its associated limit switches and complicated linkages between motor and valve. Owing to the elimination of the vapor valve in Alpha II, these designs were not adopted.

6. SLIT-CLEANER EQUIPMENT

In the operation of the mass spectrograph, material was deposited on the outlet slits of the arc chamber. Since such deposits affected the operation of the ion source, it was desirable to provide for the cleaning of these slits during operation. An electrically operated device had been designed for cleaning these slits in the Alpha II plant. The necessary electrical control equipment had been installed in one building, but the slit-cleaning equipment was not received during the time the plant was in operation.

The need for slit-cleaning equipment was eliminated eventually through the development and use of thin slits, which heated sufficiently to prevent collection of charge material.

The electrical equipment installed for use with the Alpha II slit cleaner consisted of a d-c power-supply unit to furnish power to three separate d-c motors, operated above ground by the decell potential of the system.

For the one Alpha II building in which this power supply was installed, the transformers were contained in the oil-filled tank with the vapor-valve power-supply transformer. The rectifiers used in conjunction with these transformers were mounted on the vapor-valve rectifier panel.

The two slit-cleaner transformers, each rated 60 cycles, single phase, 1.5 kva, 460/90 volts, were assembled one above the other. These transformers with their respective single-phase full-wave bridge-connected rectifiers delivered 30 amp at 60 volts direct current on a 25 per cent duty cycle. The same current was supplied with the same duty cycle at 50, 40, 30, or 20 volts by means of an autotransformer mounted in the control cabinet of the unit. The autotransformer was rated 60 cycles, single phase, 1.87 kva, 460/387/182 volts and was designed for a 50 per cent duty cycle.

The rectifier-panel assembly was mounted on insulators located on the transformer cover. These insulators provided the necessary insulation for the rectifier unit in a 35-kv d-c circuit. The secondary connections from the transformer to the rectifiers were brought out of the transformer case through these insulators to a rectifier panel on top of the insulators.

Overload protection for the unit was provided in the primary of the transformers by General Electric type CR-2824-41C temperature-overload relays with thermal elements rated 3.1 to 3.4 amp. These relays were in the control cabinet and were reset automatically after an overload occurred.

The control cabinet for the unit was mounted on the side of the transformer tank and contained the automatic control equipment necessary for the operation of the slit-cleaner motor. The control circuit for the motor was designed so that when the control switch at the control operator's location was in the closed position the circuit would function automatically to provide the following operating cycle for the motor: (1) energized by positive d-c supply, (2) deenergized, (3) energized by negative d-c supply, and (4) deenergized. Both the on interval and the off interval were controlled by separate time-delay relays and were independently adjustable between the limits of 0.6 to 0.3 sec. These time-delay relays were General Electric type CR-7504-A3 vacuum-tube time-delay relays.

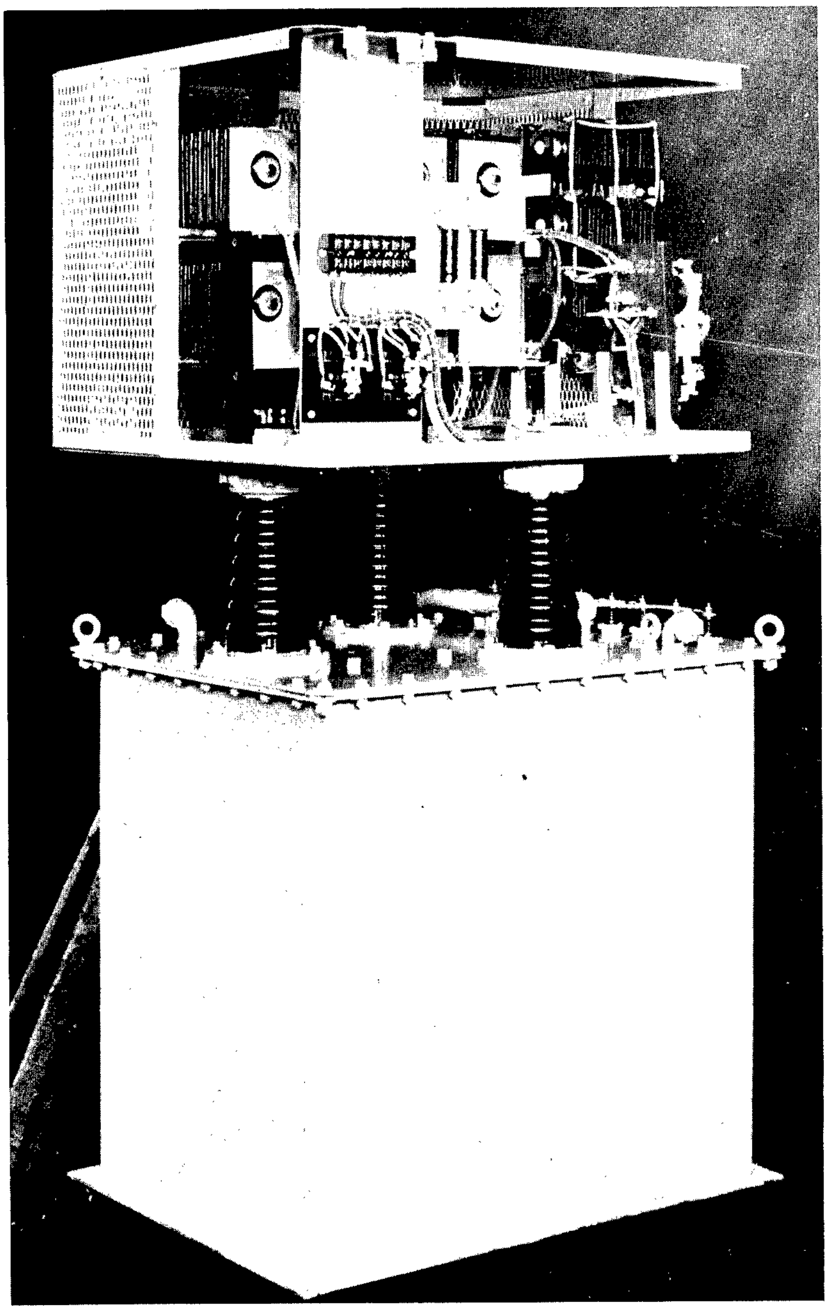


Fig. 16.1 — Vapor-valve and slit-cleaner power-supply assembly. Shield on one side removed.

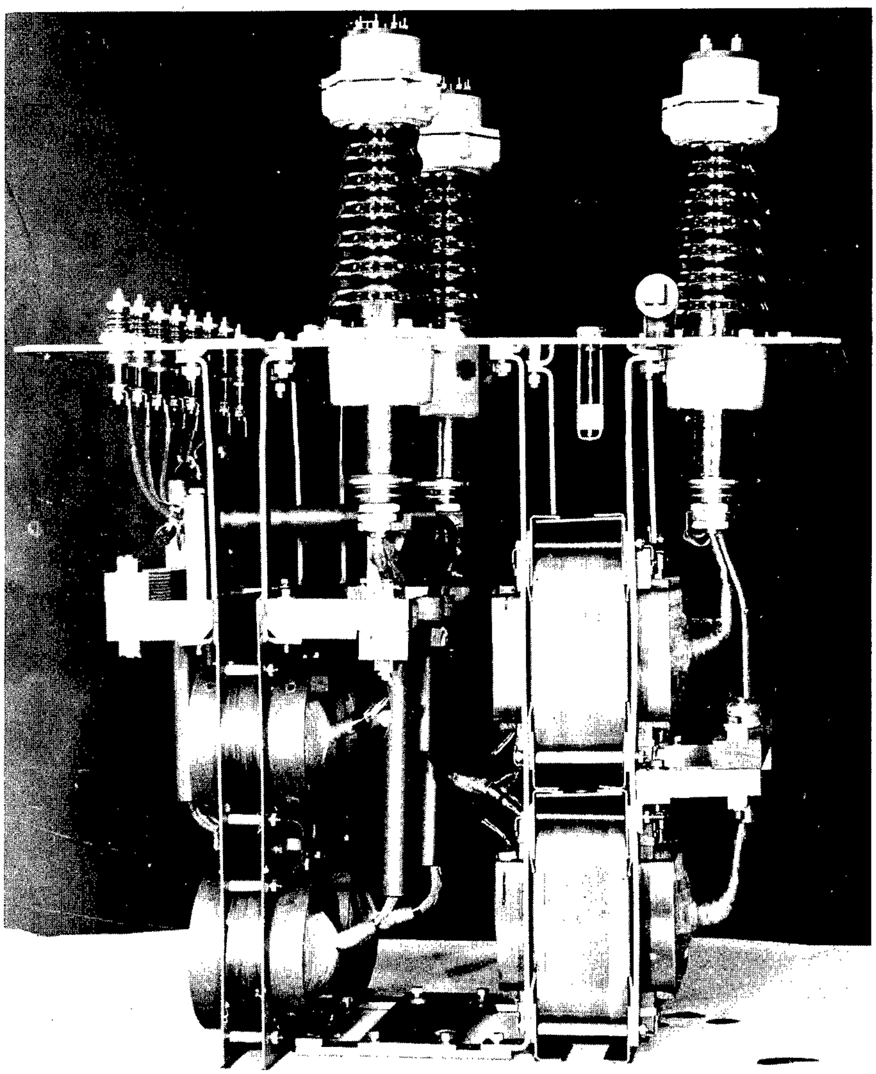


Fig. 16.2 — Vapor-valve and slit-cleaner power-supply transformer unit.

Chapter 17

ION-BEAM MONITORING

A measure of the quantity and the quality of the product received from the ion beam was needed as a control for the operation of the process. The beam of positive ions landing on the receiver was neutralized by a flow of electrons into the receiver from an outside source. A current meter placed in the conductor to the receivers measured the quantity of electrons needed to neutralize the ions received, and thus the production was measured during operation. Since two principal isotopes were being separated, two receivers were used on each beam, one for the heavier and one for the lighter isotope. The relation between the currents from the two receivers was an indication of the efficiency of the separation.

1. MONITORING EQUIPMENT AS RECEIVED

Two meters were used for each ion source, the first measuring the ion current in which U 238 was predominant and the second measuring the ion current in which U 235 was predominant. For reasons of security the equipment associated with the U 238 ion beam was known as the "Q" circuit, and that associated with the U 235 beam was known as the "R" circuit. The Q meter was a measure of the quantity of material received. The Q-to-R current ratio gave an indication of the degree of separation.

In Alpha I the carbon electrodes of the Q and R collectors were insulated from and connected to the decell liner through monitor meters located on an insulated panel in the high-voltage cubicle. This panel served as the mounting and the common return for the monitoring meters and was behind a window in the high-voltage cubicle through which these meters could be observed. Since the Alpha I mass spectrograph was equipped with two ion sources, two Q meters rated 0 to 150 ma direct current were supplied for each channel. These meters were protected from transient voltages by a 2.5-millihenry inductance

connected in series with the meter and a 0.1-μf capacitor in parallel with the meter and inductance. Two R meters having a range 0 to 7.5 ma direct current were provided. They had protection similar to that of the Q meters.

The monitor equipment for the Alpha II mass spectrograph consisted of four Q meters and four R meters. These meters were connected between their respective collector electrodes and ground. The Q meters had a scale range of 0 to 200 ma direct current, and the R meters had a scale range of 0 to 15 ma direct current. The Q meters were protected from transient voltages by a 2.5-millihenry inductance connected in series with the meter and a 0.1-μf capacitor in parallel with the meter and the inductance. The R meters were protected by a 0.1-μf capacitor in parallel with the meter.

In Beta, two Q meters and two R meters were required to operate at ground potential. The Q meter had a scale range of 0 to 150 ma direct current, and the R meter had a scale range of 0 to 8 ma direct current. These meters were also protected by a series choke of 2.5 millihenrys, the choke and meter being shunted by a spark gap and a 0.1-μf capacitor. These meters were connected from their respective collector electrodes to ground through telephone-type shorting jacks used for the insertion of additional equipment as needed.

A shutter had been provided which could be closed over the U 235 collector during periods of unsatisfactory operation to reduce contamination of the material in this collector. This shutter was operated manually, but the high-voltage-cubicle operator supervised the control of the shutter position. Since these two points were widely separated, it was necessary to provide the signaling and shutter-position indication.

A signal circuit was provided from the high-voltage cubicle to the tank position which utilized signal lights to indicate to the tank-operating crew the desired position of the shutter. Each shutter was in turn equipped with microswitches, which energized signal lights at both the tank and the high-voltage cubicle to indicate to the operating personnel the limit position of the shutter.

2. ADDITIONAL BETA MONITOR CIRCUIT

Operating experience in Beta indicated that a clearer definition of the degree of separation and reception could be determined by a separate defining electrode. This electrode was grounded through a Q′ meter which had a range of 0 to 8 ma direct current and which was protected from transient voltages in the same manner as were the other meters in the monitoring circuit. Two meters were provided

per channel and were installed on the front door of the high-voltage cubicle adjacent to the Q and R meters.

3. DECRUDDER CIRCUIT

Owing to the close spacing of the receiving pockets and electrodes, the material collected frequently caused short circuits between electrodes. Short circuits also occurred between the receiving pockets and the decell liner in Alpha I and between the pockets and ground in Alpha II and Beta. Operating experience indicated that many of these faults would clear if the collectors were allowed to cool but would return soon after the collectors again became hot. These were known as "thermal faults," and most of them could be cleared by applying an a-c potential to the short circuit. The a-c supply circuit for clearing these short circuits was current-limited to prevent excess power from being dissipated in the equipment, thus damaging the unit. The initial units for burning out such faults were portable. Since these shorts recurred as often as four times per hour, permanent burnout equipment was installed to increase production time and decrease the number of maintenance personnel required.

The permanent burnout equipment, known as the "decrudder" and installed in Alpha I, utilized an insulating transformer and a combination of contactors to disconnect the monitor meters from the circuit while applying 110-volt alternating current across the short circuit. This equipment was installed so that it could be operated by the high-voltage-cubicle operator without interrupting production. The transformer used previously insulated the beam-control regulator but had been disconnected at the time this regulator was abandoned. This transformer was rated 60 cycles, single phase, 0.2 kva, 460/115 volts. A series resistor in the secondary circuit of this transformer was used to limit the current through the short circuit to less than 2.5 amp.

In Alpha II the decrudder circuit was energized directly from one of the 115-volt supplies in the cubicle, and no insulating transformer was required since the Alpha II monitor circuit operated at ground potential. Current from this supply was limited by a series resistor consisting of four 20-ohm resistors connected in parallel. A General Electric type SB-10 switch supplied any one of the four pairs of collectors. An indicating light was connected across the series resistance to indicate the clearing of the short circuits.

The Q collector was isolated from ground for a short period of time before voltage was applied to this circuit. During this time the voltage of the Q collector could build up to several thousand volts owing to the charging of the collector by the ion beam, and it could arc through the

insulation of the collector lead to ground. This arc to ground would form a conducting path that could not be removed with the decrudder. To eliminate this type of failure the decrudder circuit was rewired so that during the switching period the collector electrode was connected to ground through a resistor of sufficiently low value so that the collector potential could never exceed approximately 100 volts.

In the Alpha II decrudder circuit, when a short occurred between two Q collectors, application of the decrudder voltage to the first Q electrode would cause current to flow through the Q meter in the second electrode circuit, destroying this meter. Two methods were suggested to eliminate this defect. The first was a remodeling of the SB-10 switch so that it would ground all the R collectors and all Q meters while applying voltage to all the Q collectors. This eliminated the possibility of current flow through a meter because of an interelectrode short. This was not tried before the Alpha II plant shut down.

The second proposed modification of the decrudder circuit provided relays whose contacts were used to shunt all the monitor meters during the time that voltage was applied to the short circuit. This circuit modification was installed in 48 channels, and the rate of failure of meters was reduced to zero owing to the operation of the decrudder. The Alpha II plant was shut down before this could be installed on a plant-wide basis.

In the Beta decrudder circuit, relays were supplied whose normally closed contacts were used to disconnect the meters from the monitor circuit, and the normally open contacts applied voltage to each of the receiver electrodes. Push buttons were provided and were connected so that the two Q electrodes could be grounded, applying potential between electrodes to burn out interelectrode shorts. Power was supplied for the decrudder circuit from a 125-volt a-c transformer located in the high-voltage cubicle. The secondary short-circuit current of this transformer was limited to 5.0 amp by means of a series resistor.

4. TOTALING AND INTEGRATING METERS

Operating experience indicated that spot checks of the Q meters did not give a sufficiently accurate indication of production. To give a more accurate indication, the ground terminals of all Q meters for a fixed group of operating channels were disconnected from their respective grounds and were reconnected to a common insulated bus. This common bus was connected through a recording ammeter and an ampere-hour meter to ground. The recording ammeter was referred to as the total Q meter, and the ampere-hour meter was referred to as the integrator. The total Q meter gave an indication of production at any given time, and the integrator gave an indication of the total

production. These two additional monitor meters were installed for all channel groups in Alpha II and Beta.

5. INTERELECTRODE SHORT BALANCER

In Beta when a meter short could not be burned out and it was desirable to continue the run, a device known as the "interelectrode short balancer" was utilized. This device was a potentiometer that could be connected into the Q and R meter circuits so that the current in these two circuits could be divided as desired. This potentiometer was adjusted to divide the currents in the Q and R meter circuits to the values that had been recorded prior to the short. The use of this device prevented the R meters from being burned out and gave a fair indication of the Q and R currents and the degree of separation.

6. VOLTAGE-LIMITING RESISTOR

Telephone-type jacks were provided in the monitor-meter circuits of the Beta channels. These jacks were used to connect the interelectrode short balancer to the monitor circuit. If a faulty jack was in the circuit, a charge could build up to a potential that would be hazardous owing to the energy of the ion beam arriving at the collector electrodes. To eliminate this, 1,000-ohm resistors were connected permanently across these jacks. If the jack failed, this value of resistance would limit the maximum potential of the collector electrode to ground to 100 volts.

7. BETA METER RANGE

In Beta the R meters had a range of 0 to 8 ma direct current, which was satisfactory for charges of low U 235 content. The adoption of charge material considerably enhanced in U 235 to increase production required a meter of greater range. The R meters were shunted to provide a full-scale range of 0.40 ma direct current. The scales of these meters were not changed. A multiplying factor of 5 was used when the scale readings were logged.

The Q meters had a range of 0 to 100 ma direct current. They were adequate for all charges used to date.

8. REMOVAL OF SHUTTER SIGNAL

With the use of Q′ electrodes for focusing, the shutters over the receiving pockets in Beta were no longer needed. These shutters were removed along with the signal circuit associated with them. This shutter-signal circuit had been used as an indicator for the logging of

production time. When this circuit was removed, a new signal circuit was installed which operated a production-time meter when the coarse high-voltage control was set above 33 kv and when arc current was flowing.

9. FLURRY SUPPRESSORS

During the operation of the mass spectrograph, recurrent high-voltage sparking would take place which could be stopped only by manual readjustment of the operating conditions by the high-voltage-cubicle operator. Such recurrent sparking was known as a "spark flurry" and resulted in a considerable loss of production time.

The suggestion was made that it might be possible to arrest automatically the spark flurries that were an inherent part of Alpha II operation by devising an apparatus that would lower the arc currents a predetermined percentage each time the total accell current exceeded a definite value. These arc currents were to be returned to normal after a fixed time delay.

Equipment was designed and constructed to accomplish this operation. After a few test runs it was concluded that the apparatus showed promise but that it did not function well enough, owing to the instability that developed in the mass spectrograph when all the arc currents were lowered or raised simultaneously.

The next approach was to modify the apparatus so that only one arc current was reduced when an accell flurry occurred. Experiments indicated that about 60 per cent was the most suitable value of reduction for the arc current. This system functioned very well on accell flurries since in nearly every case the apparatus would arrest an accell flurry automatically. It was observed that it was still necessary in most cases to reduce the emission limit of the decell regulator tube to clear decell flurries.

A decell suppressor was designed to be used with the accell suppressor. The decell suppressor automatically reduced the emission limit of the regulator tube when the decell current exceeded a specified value and returned the emission limit to normal after a fixed time delay. This arrangement, using both the accell and decell suppressors simultaneously, worked well. The suppressors would automatically arrest nearly all normal types of flurries.

Further use of these suppressors in a 12-channel special test program indicated the desirability of the following:

1. Interlocking the accell and decell suppressors so that when the decell suppressor operated the accell suppressor would also operate but would not start its timing cycle until the decell suppressor had cleared. This arrangement not only helped to clear flurries but al-

lowed the emission limit to be reduced a maximum amount without allowing the decell voltage to go out of regulation.

2. Interlocking both the accell and decell suppressors with the high-voltage breaker so that they would operate on each recycle. After a recycle this reduced to a minimum the time required to return to normal operation.

It was further noted that, when the accell and decell suppressors did not arrest normal flurries, lowering the emission limit an additional amount would clear the flurry in about 75 per cent of these cases. This knowledge led to the development of the supersuppressor circuit, which was incorporated with the accell and decell suppressors. The first supersuppressor circuit consisted of a thermal time-delay relay that was actuated after the decell suppressor had gone through three to five successive cycles without clearing the flurry. The supersuppressor would then reduce the current of an additional arc and lower the emission limit still further.

As operating procedure changed, it was noted that lowering the arc current 60 per cent would in some cases cause an erratic arc. To overcome this the circuit was revised to reduce either one arc 60 per cent or reduce two arcs 20, 30, or 40 per cent. It was found that reducing two arcs 30 per cent each gave good results for nearly all types of operation. This procedure was recommended for average operation.

Changing the accell suppressor to suppress two arcs necessitated a revision of the supersuppressor. The final model of the supersuppressor reduced the emission limit only. It was actuated after the decell suppressor had gone through approximately five successive cycles of operation. Once it was actuated, it would lock in and would not clear until both the accell and decell suppressors had cleared.

These suppressors were installed in approximately 50 out of 480 Alpha II cubicles before the plant was shut down, but they were removed when the plant was put in stand-by condition.

10. MONITOR-CIRCUIT SERVICE CONDITION

The most important precaution required in the monitor circuit was to hold the resistance of this circuit as low as possible, since the allowable drop in this circuit should not exceed 1.5 volts. This was essential because a higher voltage would cause sufficient distortion of the ion beam at the collector to cause contamination of the material. The resistance was kept low successfully in all the monitor circuits.

Throughout the plant, under normal operating conditions, the currents in the monitor circuits were less than the ratings of the meters used in these circuits. If owing to improper operation the U 238 beam was allowed to fall on the U 235 collector, the meter in this circuit

would be badly overloaded. Although the U 238 meter was not overloaded owing to the operation of the mass spectrograph, the meter frequently overloaded because of improper operation of the decrudder circuit. Interelectrode shorts requiring frequent use of the decrudder prevented proper monitoring of the equipment. Overloading resulted in a run termination if it could not be cleared by use of the decrudder. The number of shorts occurring in the monitor circuits of 384 Alpha I channels averaged approximately 250 per day. This number of shorts required an average of 28.7 servicing hours per day. Attempts were made to correct this, and, although noticeable improvement was obtained, such interelectrode shorts were not eliminated.

The service record of the monitor equipment was good; however, some trouble was experienced in the Beta equipment owing to the frequent burning out of the R meter caused by improper beam focusing. Frequent meter burnouts also occurred in Alpha II and Beta as a result of using the decrudder circuit when interelectrode shorts existed.

The jumper cables used to connect the monitor circuits to the mass spectrograph were a constant source of trouble owing mainly to improper handling. These jumpers were in a shielded flexible conduit that had a Cannon or Amphenol plug on each end. The shielding on these jumpers often became broken and frayed, and this resulted in broken insulation of the plugs. The replacement rate of these jumpers was approximately 10 per cent per month.

11. MONITOR EXPERIMENTAL AND THEORETICAL STUDY

11.1 Alpha I Recording-monitor Meter. A continuous record of the monitoring-circuit currents of Alpha I was made by installing Esterline-Angus recording milliammeters in each of the monitor circuits of several channels. These meters were mounted on a suitably insulated platform in a grounded metal cage located on top of the high-voltage cubicle. These meters were connected in series with the monitor meters and were protected from transient voltages by a choke coil and capacitor. The chart-drive motors of these meters were supplied from the beam-control-regulator insulating transformer.

During the course of this experiment these meters gave satisfactory electrical service and gave a continuous record of the operating current.

11.2 Beta Maximizing Q Meters. Experience in Beta indicated that a better definition of maximum reception could be obtained if suppressed zero-type Q meters were used. An experimental installation was made which utilized (1) a battery and potentiometer to buck out the major portion of the Q current and (2) a switching device to in-

crease the sensitivity of the Q meter. This circuit gave an expanded meter scale when maximizing the Q current. It required a device to protect the Q meter from being burned out by the reverse battery current when the Q current became zero owing to a high-voltage spark in the mass spectrograph. The circuit was not adopted for plant use because the cost and change-over time were prohibitive and because the increase in production did not warrant it.

11.3 Slugging. In the mass spectrograph the distance between the U 238 and U 235 collector pockets was 3 slugs. A slug was defined as the dimensional distance between the trajectory of an ion having mass X and the trajectory of an ion having mass X ± 1 at the point where the maximum separation existed between these two trajectories. Since the trajectory of the ion was a function of the magnetic field and the decell voltage, the diameter of the trajectory could be changed by varying either factor. The operation of shifting the decell potential by a definite amount to cause the beam to strike the collector at a fixed distance from the normal reception position was known as "slugging."

In Alpha II a method was provided for moving the U 238 beam onto the U 235 collector (a distance of 3 slugs). When the U 238 beam was maximized on the U 235 collector and then moved by a distance that was exactly 3 slugs, the U 235 beam could be maximized on its own collector.

To move the beam exactly 3 slugs it was necessary to vary the decell voltage by an amount equal to $^3/_{238}$ of the decell voltage. This was accomplished by inserting a 220,000-ohm resistor in series with the decell voltage divider to change the ratio of this divider. A push button normally short-circuited this resistor. The operation of this push button allowed the U 238 beam to be maximized on the U 235 collector and then be moved 3 slugs to its own collector.

During the routine operation of the mass spectrograph it was necessary to remaximize the Q current by adjusting the arc conditions and the decell voltage. Remaximizing each time on the U 235 collector would cause too much contamination. Owing to the erosion of the U 238 carbon by the ion beam, remaximizing on the U 238 collector would gradually shift the U 235 beam from its correct position. It was necessary to provide a method to compensate for the erosion of the U 238 carbon.

This was accomplished by inserting an additional variable resistor shunted by a push button in series with the voltage divider. This variable resistor was short-circuited by the normally closed contact of the push button, and the normally open contacts were connected across the original fixed resistor. When the push button was operated, the

fixed resistor was removed from the voltage-divider circuit, and the variable resistor was inserted.

In the operation of the modified slugger the U 238 beam was first maximized on the U 235 collector by using the fixed resistor in the slugger and then was moved to its own collector. The value of the Q current read at this time would not necessarily be the maximum, because of the erosion of the U 238 carbon, and maximizing the U 238 beam on its own collector would not guarantee that the U 235 beam was properly maximized on its collector. After the U 238 beam had been maximized on the U 235 collector and moved to its collector by means of the fixed-resistor slugger, the push button of the variable-resistor slugger was operated, and the variable resistor was adjusted to give a maximum Q current. The operation of the variable-resistor slugger compensated for the change in beam position for maximum reception which was caused by the erosion of the U 238 carbon, and the fixed-resistor operation ensured that the U 235 beam was properly maximized on its own collector. After the variable-resistor slugger had been adjusted to give the proper voltage to compensate for the erosion of the U 238 carbon, it was used to shift the beam on the U 238 collector to the point where maximum current would be received whenever it was desired to remaximize the Q current by other adjustments of the mass spectrograph.

Similar slugging experiments were made in Alpha I, but in neither Alpha I nor Alpha II was the production increase sufficient to justify installing this equipment throughout the plant.

11.4 Experimental Coulomb-meter Installation. Since production as calculated from the monitor-meter readings did not agree with chemical determination, it became desirable to use a third method of measuring production. This need resulted in the experimental installation of coulomb meters in the monitor circuits. These meters consisted of two electrodes submerged in an acid solution, the electrodes being connected in series with the monitor circuit. A flow of current through the coulomb meter resulted in a change of weight of the electrodes. This change of weight was used as a measure of the integrated current.

The results of such experiments and chemical analysis and other data formed the basis for the establishment of conversion factors to be used with the recorded meter readings to determine the amount of production achieved.

11.5 Damped Monitor Meter. Since sparking in the mass spectrograph caused wide variations in the reading of the monitor meters, a meter was required having a long time constant so that the average total Q current for the channel could be accurately determined. The

circuit tried in Alpha II consisted of a resistor placed in series with the total Q meter and ground. Across this resistor was shunted a combination consisting of a series resistor and capacitor. A voltmeter was connected across this capacitor and calibrated to correspond to a total Q current of 0 to 500 ma direct current. The over-all meter circuit had a time constant of 100 sec. No conclusive results as to the merits of this type of monitor meter were obtained during the course of the experiment.

Part III

MAGNET EQUIPMENT

INTRODUCTION TO PART III

Successful operation of the calutron requires a very uniform and well regulated magnetic field with a rather large volume. For the operation of many calutrons an economy of magnetic field is achieved by installing a number of calutrons in a single magnet. In these large magnets, vacuum tanks and magnet coils are alternately arranged. The oval arrangement of the Alpha I structures resulted in the magnets being referred to as "tracks"; Alpha II and Beta magnets were rectangular. The Alpha magnets each contain 96 vacuum tanks, but there are only 36 in each of the Beta magnets. From a production standpoint this operation of compound equipment introduced several problems. A single failure interrupts a large number of production units. All units in a track must operate at a fixed field level. The magnetic field cannot be turned off for other than major repair. All equipment used in the magnet area must be nonmagnetic, and the personnel must be trained to avoid hazards introduced by the magnetic field.

The first and major difficulty experienced with the magnets was due to ground faults. Neither the magnet coils nor the generator armatures are normally grounded. Any low resistance to ground is identified as a ground fault. More than one ground fault in the same system would, of course, lead to power losses, local heating, and serious irregularities in the magnetic field. Special equipment and procedures were developed for locating ground faults.

Since each magnet coil had about 1 henry inductance and carried a large current, the usual circuit breakers could not be used because of the very high transient voltage which would be generated when the circuit was open. Special switchgear was installed, as well as protective gaps, to safeguard against the hazards of a broken circuit.

In the operation of a calutron a constant magnetic field is required; a variation of but 0.21 per cent in magnetic-field strength will displace a uranium ion the equivalent of 1 mass unit. Monitoring circuits and magnet current regulators were designed to provide the uniform field required.

Chapter 18

DESCRIPTION OF MAGNET SYSTEM

1. MAGNET

The electromagnetic process of separating isotopes required a large evacuated volume through which a magnetic flux passed. The direction of the magnetic flux was required to be uniform through most of the volume. Welded-steel tanks in which the process ion sources and receivers were placed were connected to vacuum pumps and placed between pole faces of large electromagnets. In the process buildings the magnet coils and tanks were arranged alternately, and any such group of tanks and magnet coils was usually called a "track." Figures 18.1 to 18.3 show typical Alpha I, Alpha II, and Beta tracks in which the magnet coils between tanks can be identified by their piping connections for cooling oil. The boxlike structure running the length of each track on top of the coils housed the bus bars which carried the magnet current. The core structure between tanks around which the coils were wound was solid in Beta and cellular in Alpha.

The coils and air gaps formed a more or less closed loop, eliminating the necessity for a large iron return path for the magnetic flux. In the plant magnets the volume of the iron core could be as little as 30 per cent of the total volume of the flux path. The fields, as high as 7,000 gauss, stored very large quantities of energy in the high-reluctance 1,600- to 18,000-cu ft air gaps, the relation being expressed by the equation

$$\text{Total stored energy} = W = \frac{LI^2}{2} \times \frac{1}{1{,}000} \text{ kwsec}$$

$$= \frac{1}{2{,}000} \times 1.25 \times (7{,}500)^2 = 35{,}000 \text{ kwsec}$$

where L is 1.25 henrys and I is 7,500 amp, the approximate values for the plant magnets.

Low-resistance high-inductance coils, which formed the electrical system of each magnet, were arranged in parallel circuits with several coils connected in series in each circuit as shown in Fig. 18.4. The electrical system had no metallic connection to ground. This made possible the use of various fault-detecting devices.

The number of coils used in a track magnet was not divisible by the number of parallel circuits. Therefore to obtain currents of approximately the same magnitude in each of the parallel circuits, two of the coils of the magnet shown in Fig. 18.4 were divided into two parts so that each circuit contained a number of full coils and a single half coil. To reduce variations in field intensity from air gap to air gap due to coil-current variations, the coils around the magnet were arranged so that two coils in any circuit were separated, when possible, by a coil from each of the other circuits. For example, in Fig. 18.4 coil 1 is connected electrically to coil 5, although physically coil 1 is separated from coil 5 by coils 2, 3, and 4. Thus the field intensity in any gap tended to be the average produced by the currents from all the parallel circuits.

Continuity of service of the magnet electrical system and very accurate regulation of field intensity were required for satisfactory plant operation. Loss of regulation of the magnetic field prevented reception of isotopes while the magnetic field was out of regulation, and a loss of the magnetic field for more than a few minutes not only stopped reception but also caused certain phases of the operating cycle to be delayed much longer than the time the field was off. Since the magnetic field was common to all the tanks or channels in a track, it was about one hundred times more important for the electrical equipment in the magnet system to operate properly and continuously for all the channels than for any one channel. Therefore tests and/or work on the magnet system were required to be done while the bus voltage and magnetic field were on. A routine service shutdown for a few hours was scheduled once a year, at which time the electrical system was completely serviced so that the system would operate with minimum trouble. An electronic regulator provided regulation of coil current to provide indirect regulation of field intensity.

2. MOTOR-GENERATOR SETS

Shunt-wound separately excited generators supplied current to the magnet coils. Currents up to 4,000 amp were usually supplied by one generator, and currents around 7,500 amp were usually supplied by two generators. In certain applications, however, two 7,500-amp magnets were each supplied by four generators connected in two

parallel banks, each bank containing two generators in series. The load demands on the generators varied from 1,200 kw, 4,000 amp at 300 volts to 4,500 kw, 7,500 amp at 600 volts, depending on the type and size of the magnet being excited. The generators varied in capacity from 1,750 kw at 350 volts to 3,000 kw at 700 volts and were designed to withstand momentary short circuits. Under certain conditions it was necessary to short-circuit the generators momentarily to protect them from the stored energy in the magnet.

The generators were driven by 13.8-kv synchronous motors, which varied in capacity from 2,100 to 8,400 hp. One motor was used to drive two generators when more than one generator supplied current for a magnet. The motors operated continuously, except for the scheduled shutdowns, without requiring any unusual servicing.

The only important plant change was the installation of enclosed relays in place of auxiliary contacts on the motor-field-application contactors. These auxiliary contacts, which remained open over the long periods of continuous operation, tended to collect dust particles. Repeated failure of these contacts to close because of such dust particles prompted the change.

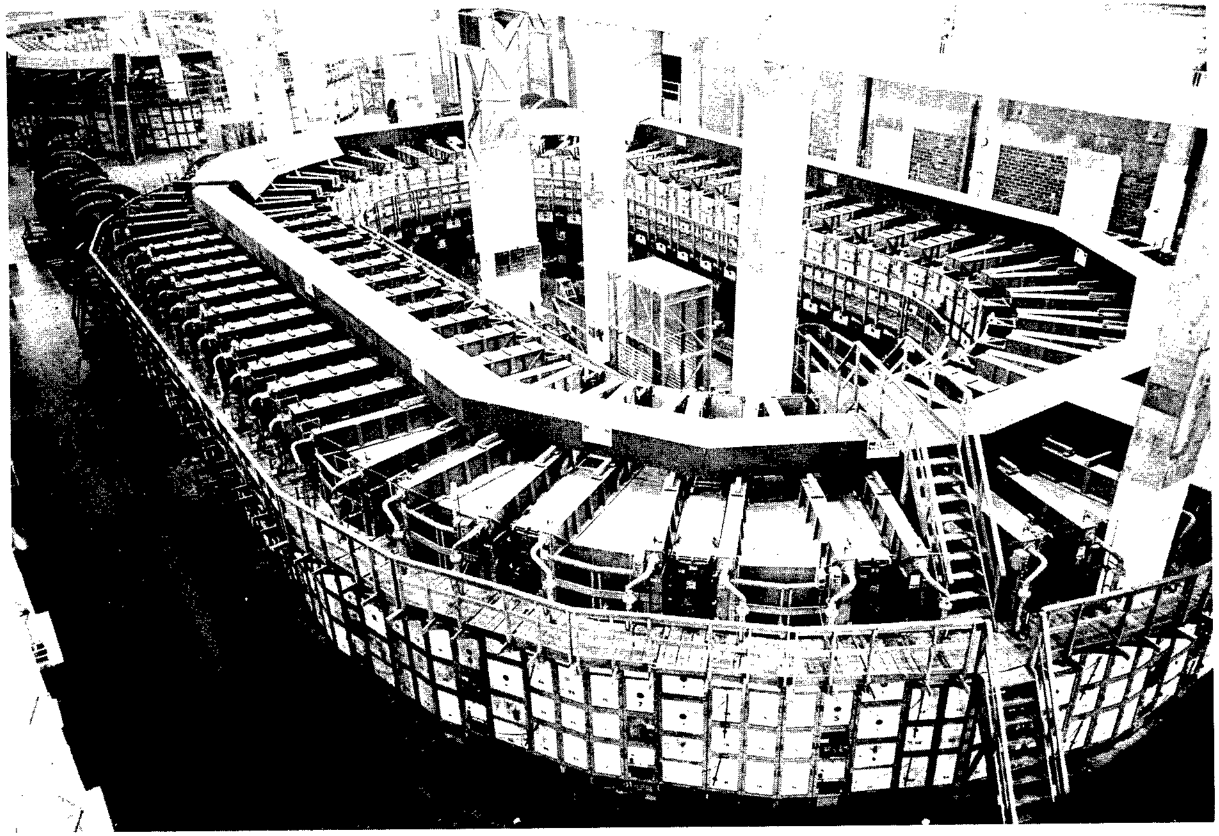


Fig. 18.1—View of Alpha I magnet.

Fig. 18.2 — View of Alpha II magnet.

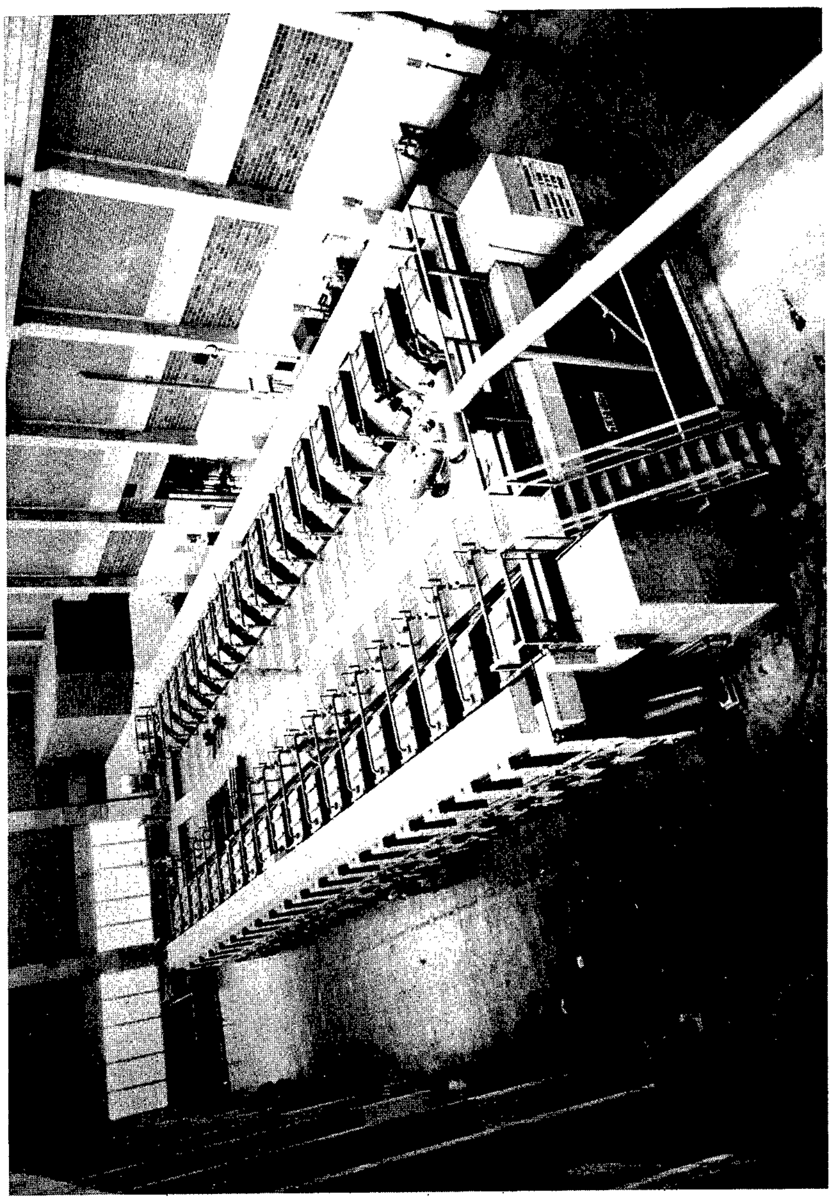


Fig. 18.3—View of Beta magnet.

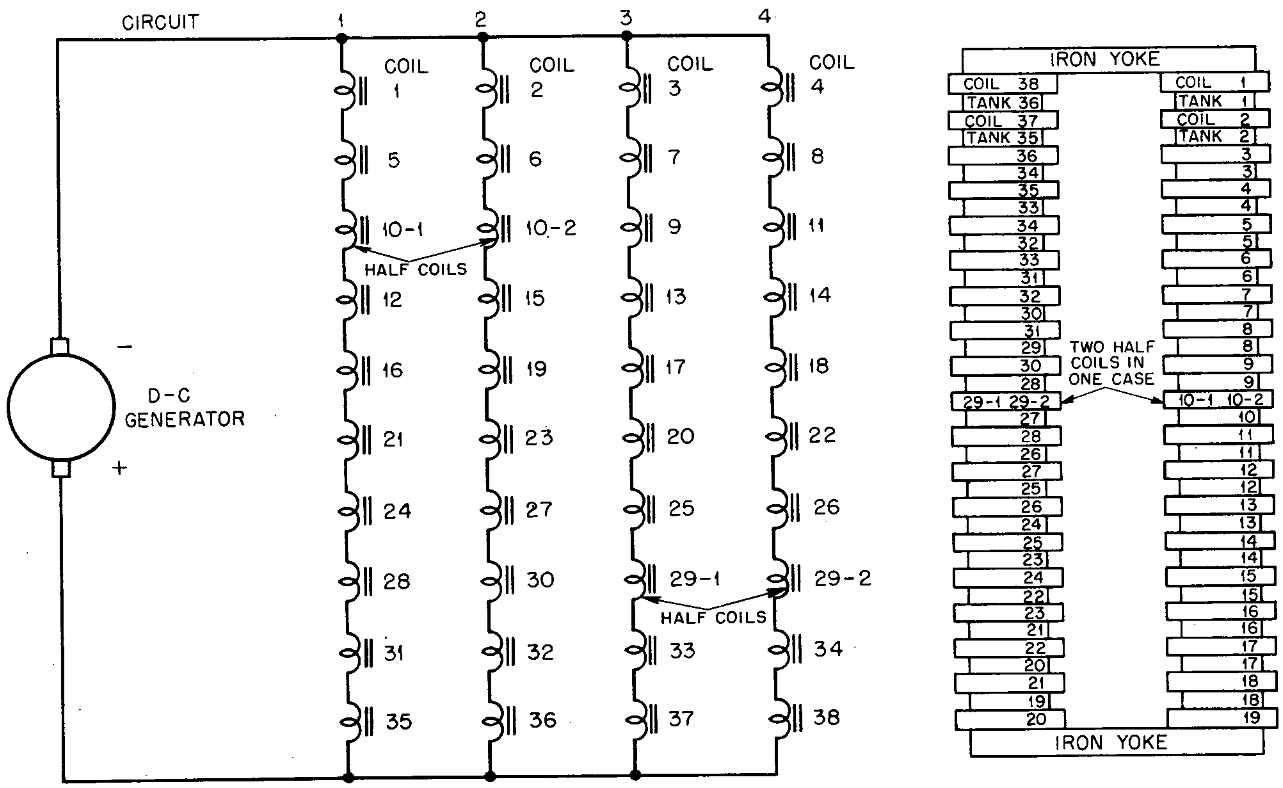


Fig. 18.4—Schematic diagram and plan view of a Beta magnet. Note that the electrical network is not grounded.

Chapter 19

DETECTION AND LOCATION OF GROUND FAULTS

1. GROUND FAULTS

A clear definition of a ground fault has never been given, but points in the magnet electrical system that have a resistance to ground of less than 10,000 ohms have generally been considered to be ground faults since tests have indicated that points with more than 10,000 ohms to ground probably will not cause trouble.

It will be noted from Fig. 18.4 that neither the magnet coils nor the generator armatures are permanently strapped to ground. The only intentional connection between the d-c system and ground is provided through a ground detector.

Neglecting for the moment the presence of the ground detector, the existence of a fault to ground at a single point of the coil system will not result in the flow of ground currents but will merely cause the generator terminals to assume definite potentials with respect to ground, depending on the location of the fault. The currents in the coils and the intensity of the magnetic field are not affected by the ground fault. Satisfactory operation of the magnet is possible, provided only one ground exists.

Trouble may arise when two or more points in the system have low resistance to ground. Currents will flow through the grounded structure of the magnet, which is then in parallel with portions of the coils. The magnitude of such ground currents depends on the location of the grounded points and on the resistances of the faults. Excessive ground currents may affect the structure in any of several ways, for example, by causing deterioration of coil insulation in the neighborhood of a fault. In addition there is strong evidence indicating that the sudden disappearance of a ground may cause very high transient voltages to be generated in the coils.

The cause of ground faults is not well understood. In the early installations ground faults were attributed to water, magnetic foreign

matter, and sludge in the oil. Because several points of low resistance to ground disappeared from the magnet system shortly after large quantities of water were filtered from the cooling oil, it has been assumed that water can be one cause of ground faults. Low resistances to ground in the magnet system have disappeared on deenergizing the magnet, lending support to the theory that a magnetic particle or a chain of magnetic particles can be held together and in place by the magnetic field so as to form a path of low resistance to ground. On one magnet a ground fault was cleared several times by shutting off the flow of cooling oil to the faulty coil, after which the ground cleared in from 0.5 to 10 min. The behavior of ground faults on this magnet seemed to indicate that some high-resistance foreign matter, such as a flake of scale, may have been causing these faults; however, similar tests on other tracks have failed to clear ground faults.

In 70 per cent of the plant magnets, ground faults have never appeared. All these were the last group installed, indicating that the causes of ground faults in magnet coils had been eliminated; however, since several precautions designed to reduce ground faults were inaugurated simultaneously, it was difficult to determine the relative importance of these precautions. Probably the best results were obtained from thoroughly cleaning the oil-cooling system before the oil was supplied to the magnet coils, thus eliminating the possibility that foreign material (such as welding slag, water, and any foreign matter that may have been left in the large oil lines) might reach the coils. Later, coils were shipped filled with oil to prevent water from condensing out of the air and collecting in the tanks. Once the wood or Masonite insulating spacers were water-soaked, considerable time was required to remove all the moisture (by vacuum pumping) from the spacers so that their resistance was acceptable.

However, despite the improvement in coils as installed, the earlier coils, comprising 30 per cent of the magnets, had grounds, and any coil can give considerable trouble if ground faults develop. Consequently it is important to have equipment and tests available for detecting and locating points having low resistance to ground.

2. DETECTION OF GROUND FAULTS

Since a ground fault is considered to exist where the resistance to ground is 10,000 ohms or less, a ground detector was developed to detect resistances in this range. The ground detector (Fig. 19.1) installed on all the magnet systems consisted essentially of a potentiometer connected across the load bus with the slider connected to

ground through a zero-center-scale recording milliammeter. The magnet coils, ground-fault resistance, potentiometer, and the milliammeter formed a bridge circuit. A deflection of the meter occurred only after the ground resistance had decreased to a few thousand ohms. Therefore a deflection of the meter indicated the presence of a ground fault.

In order to detect fault resistances of several thousand ohms, the detector was necessarily very sensitive to much lower fault resistances and thereby allowed very large currents to flow through the meter circuit. These large currents were objectionable not only because the milliammeter would be damaged, but also because the interruption of such ground currents might cause high transient voltages to be developed in the coils. An overcurrent relay set to open at 75 ma was inserted in series with the meter to prevent large ground currents from damaging the detector or magnet system.

In using the ground detector with a magnet coil that supposedly was without ground faults, the routine practice was to leave the potentiometer set at center scale. Under these conditions the meter reading was zero so long as a ground fault did not develop, and any deflection from zero was a definite indication of a ground fault. However, the absence of meter deflection did not completely guarantee freedom from faults since a fault that happened to develop at just the right point would not cause a deflection of the meter. This point was the balance point for the routine center-scale potentiometer setting. It was plant practice to make hourly checks on the possibility of a ground at this one point by moving the potentiometer an arbitrary amount to either side of center scale and watching for meter deflection.

On a magnet coil that was known to have one or more ground faults of a relatively stable character, the ground detector was used in similar fashion. In this case the potentiometer setting for zero meter current was at the balance point, irrespective of its position on the scale. The routine practice then was to leave the potentiometer set at the balance point of zero meter current, except for the hourly checks. Any change in the magnitude of current shown by these checks or any shift in the zero-current setting indicated some change in the number or nature of the ground faults of the magnet coil.

In watching ground faults of a changing or unstable character, the ground detector was used much as described above. Of course the changing situation meant changing zero-current settings and usually called for more frequent checking. In addition there was the possibility of using the recording milliammeter, with the potentiometer set somewhat off balance, to show times at which ground faults cleared or shifted location.

Some ground faults appeared for a few minutes, some for a few days, and some remained from the time the plant went into operation. Although some grounds remained at the same point for months, others appeared to float from point to point and finally to return to the point at which they started. Material causing ground faults may shift from point to point, but a fault that appears to shift from point to point and finally to return to the starting point is probably the result of shifting combination of permanent and temporary ground faults.

The ground detector, though it detects the presence of a ground, indicates only partially the location of a fault with respect to the load buses. A standard high-resistance d-c voltmeter could obtain the same indication, but the circuit of Fig. 19.1 was a more convenient permanent installation. Either arrangement singled out a group of coils that included one in each parallel branch, one or more of which had the fault.

3. LOCATION OF GROUND FAULTS

As shown above, the ground detector indicates the presence of a ground fault but not its location in the electrical system. It would be a simple matter to measure the resistance to ground at the magnet terminals with an ohmmeter if the magnet could be deenergized. Each coil would then have to be disconnected from the electrical system, and separate measurements would have to be made to isolate the coil that contained the ground fault. Such a procedure would require considerable time and man power, and since the magnets were scheduled for only one brief shutdown per year, this method of locating a ground fault was not practical.

A method of locating a point of low resistance to ground in the electrical system of an energized magnet was developed and used with very good results. Several volts commutator ripple (about 2,100 cycles) appeared across the magnet terminals along with the d-c voltage. When a point along one of the parallel circuits was grounded, the d-c voltage to ground at a corresponding point in each of the other parallel circuits was zero; the voltage to ground along any parallel circuit of coils would increase from zero at the fault to a maximum at the load bus; and the polarity of the voltage at any point to ground was determined by the polarity of the load bus on that side of the fault. Alternating-current voltages along each parallel branch would assume amplitudes similar to the d-c voltages if only one fault was present in the system. If two faults for a-c voltages existed, the a-c voltages in the parallel circuit containing the faults would differ from the voltages at similar points in the other parallel circuits. Assuming that a

ground fault was nearer the positive bus, then if a large condenser was connected from the negative bus to ground, two faults would exist for alternating current and one for direct current. The d-c voltage distribution would not be disturbed by the presence of the condenser, but the a-c voltages along the parallel circuit containing the ground fault would be a maximum at the positive bus, zero at the fault, and zero all the rest of the way to the negative bus. In all the other parallel circuits the a-c voltages to ground would be a maximum at the positive bus and would fall off to zero at the negative bus.

The above effects indicate that there was no difficulty in locating a coil containing a ground fault because the ripple voltage to ground was much less at the point that was grounded than at any similar point in the other ungrounded parallel circuits. In general, when the ripple voltage was referred to above as being zero at the fault, the assumption was made that the ground-fault resistance was zero. Ground faults with resistances up to 1,000 ohms could be located using this method.

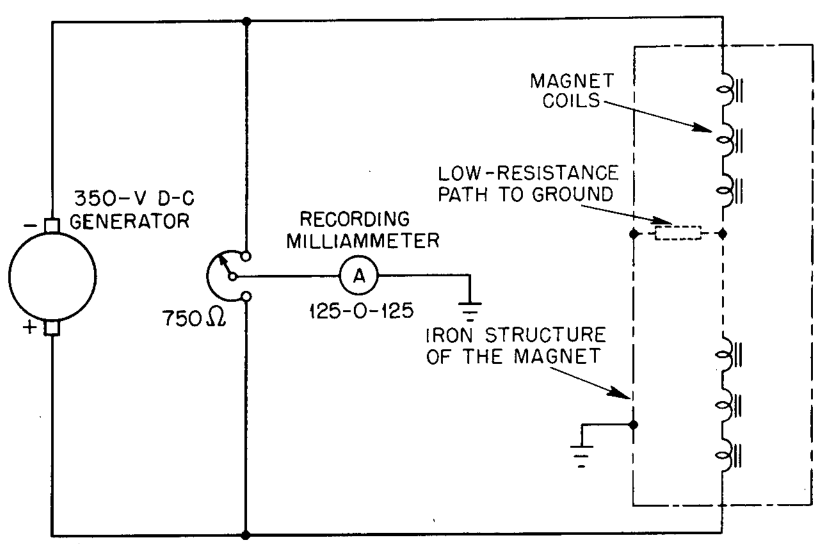


Fig. 19.1 — Simplified schematic diagram of a ground detector.

Chapter 20

DIRECT-CURRENT SWITCHGEAR AND PROTECTIVE EQUIPMENT

1. LOAD-CURRENT SWITCHING ARRANGEMENTS

Currents in the magnet coils could not be switched in the usual manner using breakers because very high transient voltages would be generated in the magnet coils if the currents through the coils were suddenly changed. Each magnet coil had an inductance of about 1 henry, and if the currents of the order of 1,000 amp were changed suddenly, very high transient voltages would be generated. The magnitude of these voltages is determined by the value of the inductance and the rate at which the current changes. Therefore any switching arrangement considered for switching the magnet current had to take into account the rate of change of magnet current.

A sudden application of voltage across the coil terminals did not cause a high transient voltage to be generated in the coil but merely caused the current to build up exponentially to a maximum value, the speed with which the current increased being determined by the values of inductance and resistance of the coil. The final value of coil current was determined by the resistance of the coil and the voltage across the coil. Similarly, a sudden removal of voltage from across an inductance would not cause high transient voltages to be generated in the inductance if the circuit for the coil current was undisturbed.

The initial magnet electrical systems (the first two magnets) were designed in general along the lines used by industry in large current installations. In Fig. 20.1 it will be observed that the magnet terminals were connected to a load bus that could be isolated from the generators by breakers and disconnect switches. A discharge breaker in series with a current-limiting resistor was connected across the load bus. To energize the magnet, the disconnect switches and positive and negative breakers had to be closed and the discharge breaker had to be open.

Once the magnet was energized, the breakers could not be opened without providing a path for the magnet discharge current. Therefore in removing current from the magnet coils, the positive breakers were first opened by manual operation, series resistors being inserted in the load-current circuit to reduce the load current for a given generator output voltage. Excitation voltages to the generator fields were removed automatically when the positive breakers opened, further reducing the magnet current by reducing the generator output voltage. The discharge breaker was closed automatically when the positive breakers opened, thus paralleling the magnet with a resistor to provide a discharge path for the magnet current before the negative breakers were opened.

The negative breakers were originally set to trip automatically when the discharge breaker closed, but the negative breaker with automatic trip constituted a hazard owing to the possibility of accidental tripping while the magnet was energized. For this reason the automatic tripping was removed and the breaker was arranged for manual operation only. The disconnect switches presented a similar hazard in that an attempt might be made to open the switches while the magnet was energized. To prevent such an attempt the switches were bolted closed.

The electrical system used on all but the first two magnets was of the type shown in Fig. 20.2. The magnet was permanently connected to the generator thus preventing the possibility of opening the magnet-current circuit while the magnet was energized. The only way the generator could be isolated from the magnet was by means of disconnect links, which were, in effect, sections of the load bus that could be unbolted and removed. Instead of a discharge breaker and resistor, a 100,000-amp circuit maker was provided as a discharge path for the magnet current.

During normal operation the circuit maker was left in the open position, and the magnet was energized by exciting the generator field to provide generator output voltage across the magnet terminals. To deenergize the magnet, the generator field voltage was removed so that the generator output voltage would decrease to a minimum and allow the magnet current to decay to the residual output of the generator. If the magnet circuit was to be opened or if the magnet was not to be energized for several hours, the circuit maker was usually tripped closed after the magnet current decayed to a few hundred amperes. The only time the circuit maker was closed with the magnet coils carrying normal current was when the magnet was deenergized by the action of armature-flashover relays or by a manually operated emergency switch.

The generator field voltage was removed at the same time the circuit maker was tripped; thus, momentarily, the generator had to supply short-circuit currents. However, the generators were designed to withstand such momentary short-circuit loads; and the electrical system, shown in Fig. 20.2, did not require that any of the equipment operate under conditions for which it was not designed.

Such a system not only eliminated all breakers and disconnect switches that would have required a certain amount of attention but at the same time provided protection for the magnet and the generator. The short across the magnet ruled out the possibility of opening the magnet-current circuit and also prevented the stored energy in the magnet from feeding back into the generator. Normally the discharge current could flow through the generator armature without any harmful results, but if a fault existed in the generator armature, the short-circuiting device prevented the stored energy in the magnet from reaching the fault.

Twenty-one of the twenty-three magnet electrical systems used in the plants were of the type shown in Fig. 20.2; the other two were of the type shown in Fig. 20.1. The system that was completely free of breakers and disconnect switches was very dependable, required much less attention than the system using breakers, and definitely showed that breakers and disconnect switches were not only undesirable but unnecessary.

2. PROTECTIVE GAPS

Inductances connected in series, as in any one of the series circuits of coils in the magnet electrical system, generate high transient voltages under conditions of discontinuous flow of current in the coil circuit. A discontinuous flow of current can result if a shorted coil clears while in a series circuit. It may be assumed that, while the coil is shorted, it carries zero current whereas the other coils carry normal currents of about 1,000 amp. If the short is removed, all the coils must pass the same current, and when the current changes very rapidly from zero to several hundred amperes, high transient voltages will be generated in the inductances to impede the current change.

The magnitude of such transient voltages depends only on the inductance of the coil and the rate of change of current through the coil, but since the rate of change of current through the coil depends on the time required to remove the coil short and on the effects of stray capacitance across the coil, it is difficult to estimate the magnitude of these transient voltages. The picture is further complicated by the fact that the inductance of an iron-core coil decreases very rapidly with an increase in frequency. Tests have indicated that the

inductance of a magnet coil changes from 1 henry at zero frequency to about 0.07 henry at 60 cycles. Just how much this effect reduces the peak values of the transient voltages is not certain, but the reduction may be appreciable.

The necessity of protective gaps was more or less assumed and was never proved experimentally on any of the plant magnets. A test that would involve generating transient voltages in the magnet coils was never given serious consideration because the early magnets had several low-resistance points to ground, and tests that would in any way disturb these faults were prohibited. Nevertheless, such a lack of fundamental information concerning the behavior of the magnets under fault conditions left many questions unanswered. Were the protective gaps necessary? Were the troubles caused by gap failures more serious than the high transient voltages? Some have felt that the magnet system would have functioned much better if the protective gaps had not been used; such opinions were not entirely guesswork because some fairly large magnets have operated for years without protective gaps.

Protective gaps were installed across all the CEW-TEC magnet coils. The gap did not interfere with the system when operating properly on normal voltages but would break down at a voltage much less than the breakdown voltage of the coil insulation. It was intended that the gap would fuse together or stay shorted once it had flashed over and would conduct generator short-circuit currents in case all the gaps in a circuit broke down at the same time.

The gap shown in Fig. 20.3 was initially installed in 35 per cent of the plant. It consisted of two copper disks 6.75 in. in diameter separated by a mica ring spacer 0.015 in. thick. A copper mounting bracket was fastened to each disk, and the whole assembly was held together by a bolt through the center of the disk, one disk being insulated from the bolt. The effective air gap was 0.015 in. with a cross-sectional area of approximately 11.5 sq in. The gaps were designed to operate at 100 volts direct current with a minimum breakdown voltage of 1,200 volts and with a voltage of not over 1,800 volts required for breakdown. Also the gaps were designed to fuse together when a breakdown occurred, thus completely shorting the coil to prevent further disturbance.

In addition to the protective gap across each coil, a single and a double gap were connected across the generator bus, the double gap having its center tap connected to ground. These protective gaps were similar in construction to the coil gaps but were rated at 700 volts direct-current working voltage with a minimum breakdown of 1,800 volts and a maximum required voltage for breakdown of not over 2,400 volts.

Gap flashovers were a constant threat to production. Since a short could not be removed while the magnet system was carrying current, the magnet was deenergized each time a flashed-over protective gap was replaced. Although a gap could be replaced in a few minutes, considerable production time and equipment were involved each time a gap was replaced because the magnet was a common element in a large number of production channels.

During the first two weeks of operation about ten gaps flashed over. Random gap flashovers during any later two-week period of operation were never so numerous. If gap breakdowns had continued at this rate, production would have been materially reduced. The gap-breakdown rate following the first two weeks of operation reached a comparatively low value of three gap breakdowns on one magnet in a year. Such a sharp change in the breakdown rate may have been due to the removal of several coils that contained ground faults. It may be that several of the protective gaps installed initially were unable to function properly under normal plant operating conditions and needed only to be replaced.

When more than one ground fault is present in the magnet electrical system, ground currents will flow. The magnitude of these currents depends on the difference in potential between the grounded points as well as on the resistance of the ground faults through which the currents pass. Should a ground fault suddenly disappear, the ground current that is being by-passed around one or more coils will suddenly cease flowing through the ground fault and will have to flow through the coils. This shunted current has the same effect as current that shunts a coil when a gap is shorted, except that the ground currents are usually smaller. In either case discontinuous currents flow in the coil circuit and may cause high transient voltages to be generated in the magnet coil.

Although tests were never made to determine the magnitude of transient voltages generated when a short is removed, two accidental ground faults on the magnet electrical system have shown that the removal of a ground fault will cause protective gaps to flash over. In one instance a No. 16 wire was accidentally connected from the magnet load bus to ground. This resulted in the breakdown of all the gaps in one parallel circuit and two gap breakdowns in another parallel circuit. Since the wire was completely vaporized, there was no way of knowing how much current the wire had delivered to the ground fault or whether the gaps flashed over before or after the wire evaporated. It seems probable that the removal of the ground fault set up the disturbance. To further complicate the general picture of how ground faults can contribute to the generation of high transient

voltages, the gaps that failed in the accidental grounding of the magnet system were in a parallel circuit that was thought to be free from ground faults.

There has never been a logical explanation of why gaps in a parallel circuit free from grounds flashed over and gaps in the parallel circuit containing a ground were in no way affected by transient voltages. Several months before the accidental grounding of the magnet system already mentioned, the same magnet was grounded accidentally in a similar manner and with similar results. In the latter instance all the gaps in another parallel circuit flashed over, and again the circuit was thought to be free from ground faults. On the other hand, ground currents up to 100 ma were broken on numerous occasions without causing a gap to flash over. It is obvious that the data on ground faults and their relation to high transient voltages in the coils are incomplete.

Random gap flashovers in the first three magnets numbered about three flashovers per magnet per year; the succeeding fourteen magnets had a total of only three flashovers in a year. The sharp reduction in the rate of failure of protective gaps occurred simultaneously with the installation of magnets that were free from ground faults and with the installation of redesigned protective gaps. Since gap breakdowns were much more frequent in magnets with ground faults (there was some indication that gap breakdowns could have been caused by the rapid disappearance of ground faults) opinion has remained divided as to whether the reduced rate of breakdown was due to fewer ground faults or to improved gap design.

The gap (Fig. 20.4) installed on the later magnets was essentially the old gap with two major changes as shown in Fig. 20.5. Both changes were to eliminate gap breakdowns due to the reduction of the effective gap length by external stresses.

Examination of the old-style gaps that had broken down indicated that most of the gaps flashed over near the center of the disk, indicating that the gap length at the center of the disk was shorter, although the gap spacing was supposed to be the same over the entire face of the gap disk. The old-style gap was rigidly mounted across the coil terminals by an angle bracket rigidly fastened to each disk. External force transmitted through the rigid mounting brackets could possibly apply a large enough force to the center region of the disk to reduce the air-gap spacing in this region. To eliminate this possibility one mounting bracket was redesigned and made into a flexible lead.

The second precaution taken to ensure an accurately spaced air gap was to cut back the face of each gap disk $\frac{1}{64}$ in. over the center portion

of the disk, leaving a narrow accurately spaced ring near the mica spacer. Referring again to Fig. 20.5, it will be observed that the spacing near the center of the disks could vary appreciably before the spacing between the two narrow rings was affected. The new gap maintained more closely a predetermined critical air-gap spacing and was assumed to have eliminated most of the spurious gap flashovers.

Unfortunately the new gaps were never installed on a large enough scale on the magnets containing ground faults to establish clearly a rate of failure for the new gaps. One magnet using the old-style gaps which had always had one ground fault never had a gap breakdown; two other magnets which were also using the old-style gaps and which had intermittent ground faults never had a gap breakdown. The rate of gap breakdown was reduced to a fairly small value, but it was difficult to estimate how much any one factor contributed to this reduction. Although the rate of flashover of gaps was much smaller than before, there was still a need for the instruments and procedures used in locating a fused gap. The period between gap breakdowns may be much longer, but when a breakdown does occur, the fused gap must be detected, located, and removed in a minimum time if the effect on production is to be held at a minimum.

The actual critical breakdown section of the air gap is not visible from the outside, and in most cases a gap will flash over and fuse the gap disk together without disturbing the outside of the gap structure. Thus a shorted gap and a normal gap have the same appearance from the outside and cannot be distinguished by visual inspection. Even if visual inspection could determine the condition of the gaps, visual inspection was not practical under the system of gap mounting in use because the protective gaps were mounted directly across the coil terminals and were so covered by the protective bus duct that they were inaccessible for routine visual inspection. Straightforward use of an ohmmeter or Megger cannot reliably indicate the condition of the gap so long as the gap is connected across a coil, either when the coil is energized or deenergized. Naturally, so long as the coil is energized, an ohmmeter cannot be used, but the voltage across the gap may be measured to indicate the condition of the gap.

Since the voltage across a fused gap is near zero and since the voltage across a normal gap is nearly 100 volts, the voltmeter method of locating a fused gap gives a very positive indication. The voltmeter must be used at a safe distance from the stray magnetic field, necessitating the use of very long voltmeter leads. The long leads not only require an extra person for reading the voltmeter but also increase

the possibility of accidentally grounding the magnet electrical system. Therefore the voltmeter method of locating a shorted gap is seldom used.

There are ways of detecting shorted gaps which depend on the fact that the coil itself is shorted by the fused gap. For example, the relation between magnetic field and operating value of high voltage can serve this purpose. For a normal magnetic field the voltage required for optimum production was about 38 kv. Any channel that operated at a voltage appreciably different from this had a magnetic-field intensity that was not normal. A short across one coil will stop production on the tanks adjacent to the shorted coil by causing the magnetic field to be too low for operation using the standard plant voltage supplies; the second tank on each side of the coil will have a magnetic field of sufficient intensity for the channel to operate at the reduced voltage of about 24 kv, and the third tank on each side of the shorted coil will operate at about 30 kv. The high voltage for the fourth tank will be about normal.

Other tanks are also disturbed by the increase in magnetic field, owing to the increased currents in the parallel branch that contains the shorted coil. Since this branch conducts more current than any of the other parallel circuits, each tank beside a coil that is in series with the shorted coil must operate at a higher voltage, about 40 kv. A shorted coil is therefore very easily identified by the optimum operating voltages of the various channels that use the same magnet.

A shorted coil could also be detected by observing the temperature of the coils, because, without current in the coil winding, heat loss was eliminated and because the temperature of a shorted coil was less than that of a normal coil. Coil temperatures were recorded about once an hour in standard plant routine. This check was not a positive indication of the condition of the gaps, but it was useful in spotting trouble.

Gap flashovers often occur in conjunction with an emergency shutdown. At such times an immediate inspection of the protective-gap temperature will give a fairly good indication of a fused gap because the gap that is carrying current will be warmer than an open gap. However, the gaps and bus structures were covered with a protective covering that made the gaps almost inaccessible.

A simple portable device was developed for identifying a shorted gap by electrical measurement. This device could be used without disconnecting the gap from the coil terminals but only when the magnet was deenergized. A long test probe was provided that was capable of making contact with each side of the gap without having to disturb the protective covering over the gaps. The device was es-

sentially an a-c generator with which the impedance existing between the terminals of a gap could be measured. If a gap is fused together, the impedance between its terminals is evidently very small. If the gap is not shorted, the impedance will be approximately that of the coil to which the gap is connected. At the frequency of the test generator (about 110 cycles) a coil has a total impedance of the order of 15 ohms. It is therefore a simple matter to differentiate between a shorted and a normal gap by an impedance indication.

As shown in the schematic diagram of the unit (Fig. 20.6), a test signal of 6.5 volts was generated from dry cells through the action of a vibrator and two transformers. The signal was applied to the gap to be tested through a series resistor. A voltmeter mounted on the unit measures the voltage appearing across the gap and gives the desired impedance indication. The meter reading was several volts for a normal gap and zero for a shorted gap.

3. PERSONNEL PROTECTION AGAINST MAGNETIC FIELDS

Protection of personnel from high-intensity magnetic fields was accomplished by enforcing a few simple safety rules. All employees were warned against carrying magnetic material into the magnetic field because such material, tools or other objects that contain iron, would be acted upon by a large force that attempts to locate the magnetic material where the field is a maximum. New employees were often shown how difficult it was to hold a small iron object such as an iron penny in the magnetic field. Nonmagnetic tools were provided for work that had to be done near the magnet. The magnets were marked with signs that warned workmen not to bring magnetic objects into the field, and constantly blinking red lights further emphasized the presence of a danger zone.

The warnings helped to protect the equipment that might be damaged by the field as well as to protect the workmen from injury. Additional warning signs cautioned the workmen not to bring watches or electrical meters into the field because the instruments would be damaged by high-intensity fields. A red line was painted on the floor several feet away from the magnet, about the 4-gauss line in front of the gaps, indicating the danger zone for instruments and magnetic material.

When a channel was in operation, the area in front of the air gaps was enclosed by a protective covering to prevent injury to personnel from the high voltage associated with the process units in the air gaps. The stray field was about 25 gauss in the region near the covering and was therefore close to the critical area where very large magnetic objects might get out of control and be rapidly drawn into the field. The field intensity increased rapidly from about

25 gauss at the protective barrier to about 5,500 gauss in the air gap near the edge of the core, a distance of 3 or 4 ft. An object that might be handled near the barrier in the 25-gauss field could get out of control a very short distance inside the barrier because of the much higher stray field intensity.

There was little physical warning of the presence of a large magnetic field from the forces on the magnetic object because these forces were relatively small even 4 or 5 ft from the magnet. But as the object was moved closer to the magnet, the forces increased rapidly, and the sudden increase in force might have been sufficient to overcome the grip of unsuspecting persons. Or, if the employee was able to hold on to the object, the forces might have been large enough to pull the object and the person up against the magnet pole face.

In thousands of man-hours spent near the magnets in strong magnetic fields, only one serious lost-time accident occurred. In this case an employee lost a finger. A few less serious accidents occurred. In one instance a careless worker disregarded the warning signs, walked into the field with a magnetic object, and was immediately pinned against the magnet in such a way that he could not be freed until the magnet was deenergized. Fortunately the employee was not seriously injured, but had he lost his hold on the metal plate he was carrying, another nearby employee would have been seriously endangered. In another instance, a man formerly in the military service complained of severe pain when he was in the magnetic field. He was examined and was found to be suffering from the movement of a piece of steel shrapnel in his body. Accidents involving personnel and equipment caused by the presence of high-intensity magnetic fields were very few.

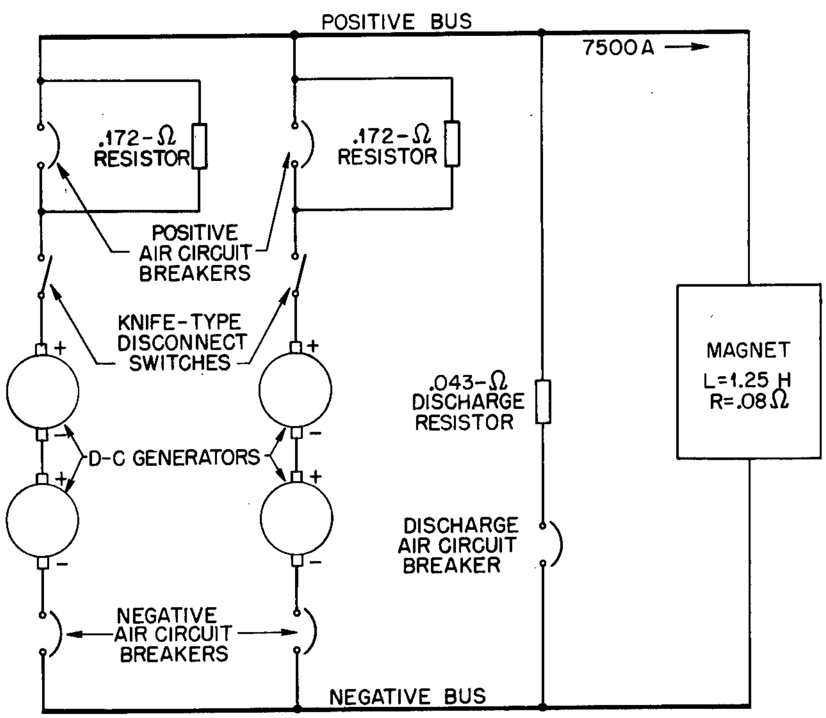


Fig. 20.1—Switching arrangement used in the first two plant-magnet installations.

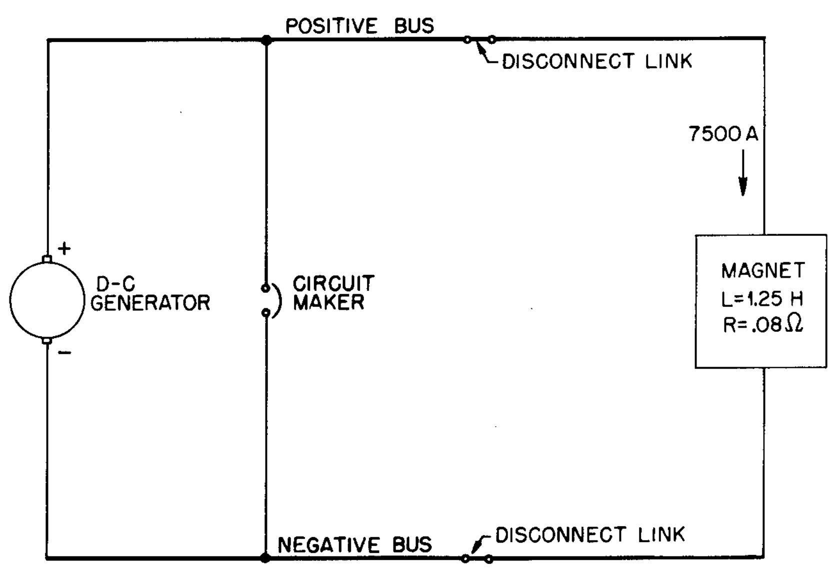


Fig. 20.2—Switching arrangement used in all but the first two plant-magnet installations.

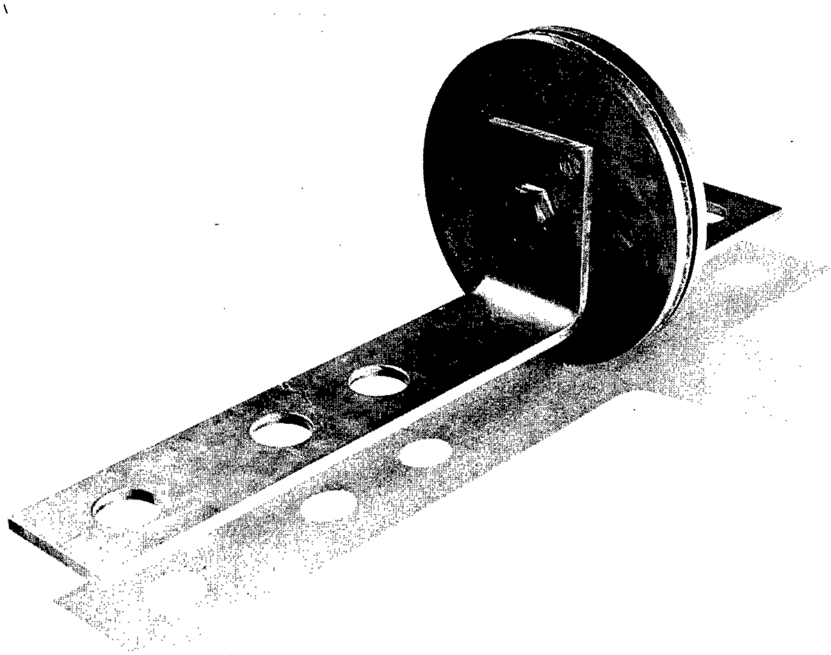


Fig. 20.3—Old-style protective gap.

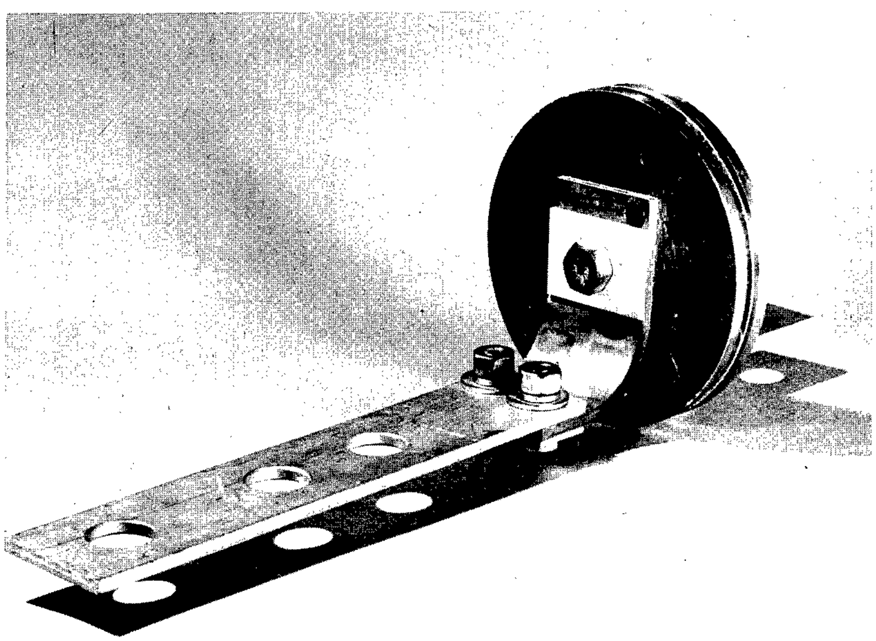


Fig. 20.4 — Improved protective gap.

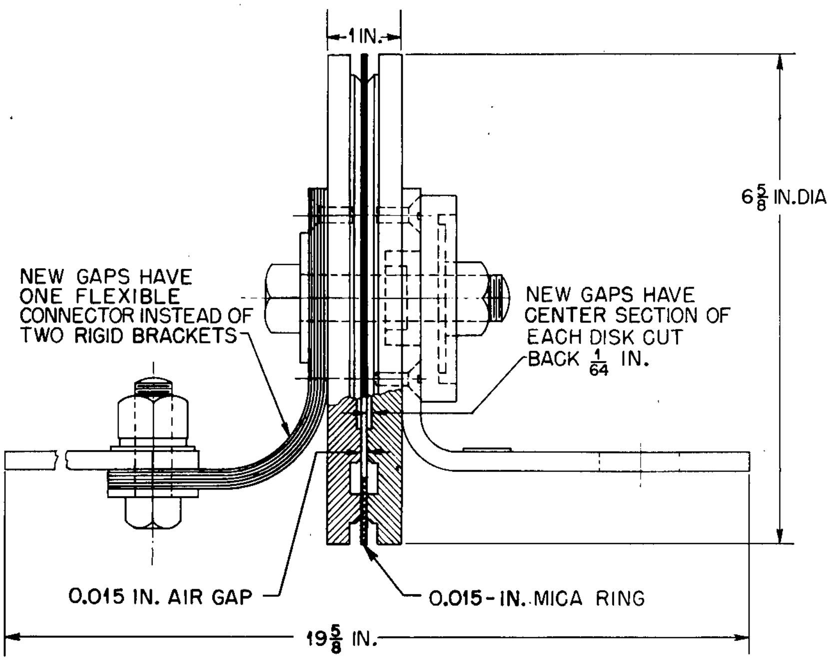


Fig. 20.5—New protective gap, noting changes in old style.

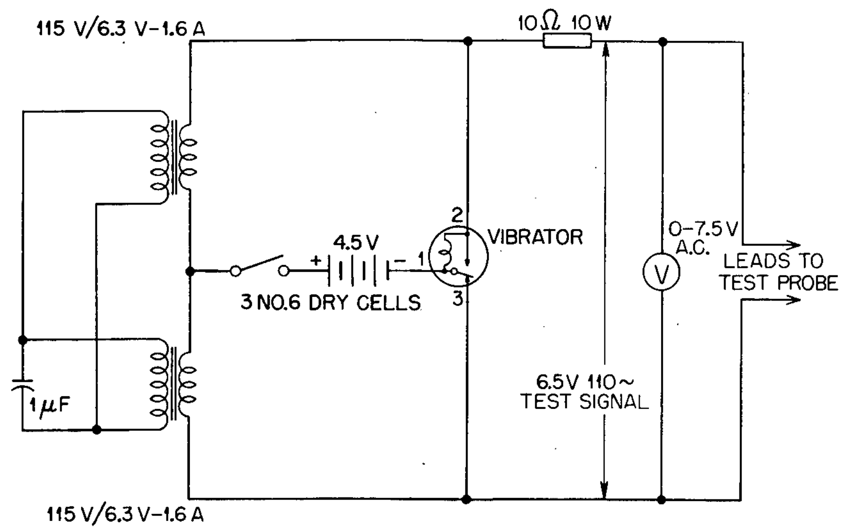


Fig. 20.6—Schematic diagram of a gap tester.

Chapter 21

CURRENT MONITORING

1. CURRENT RECORDERS

The process equipment of the electromagnetic plant was composed of a large number of channels all operating simultaneously to carry out the same process. Since the magnetic field of any given magnet was an element common to a large number of these channels, it was necessary to keep a close check on the intensity of the field of each magnet. A visible change in production will result from a 1-part-in-2,000 change in magnetic-field intensity, and as a result the field intensity was required to be held much closer than this for periods which were long when compared to the time taken between operator adjustments of the accelerating voltage or other operating variables.

Magnet-coil current was regulated instead of field intensity because a current shunt could be used to obtain a signal for a regulator. This would be much easier than developing a device responsive to field intensity. Furthermore, even if it were easy to measure field intensity, it would have been practically impossible to find a place in the magnet that could be used as a reference field for all the air gaps. If current in a coil near the reference gap were disturbed, the effect would be transmitted to all the gaps by the regulator system in an effort to keep the magnetic field constant in the reference gap.

The degree of current regulation is usually expressed in terms of the current variation over a 1-hr period. That is, if the current is to be regulated to 1 part in 4,000 in a magnet carrying 8,000 amp, the current must not vary more than 2 amp over a 1-hr period. Current regulation to 1 part in 5,000 was considered adequate for proper plant operation. A meter was required that would indicate, and perhaps record, current variations in this range.

Magnet-current variations from day to day or week to week were also of interest when an attempt was made to operate the plant at optimum magnet currents. Divergence of opinion existed as to whether

magnet currents should be held to an absolute value with very narrow limits of variation over long periods. As a result suppressed-zero meters were developed.

A standard switchboard meter was used to indicate magnet currents, but this type of meter cannot be read much closer than 1 per cent full scale. In order to get a more accurate indication of day-to-day changes in magnet currents, it was necessary to have a more sensitive meter. D'Arsonval meters with the desired sensitivity, 5 mv full scale, were not available. Commercial suppressed-zero ammeters in which the scale covers about 10 or 15 per cent of the full current range were not available. Suppressed-zero ammeters could be built to give a full-scale deflection for a 1,000-amp change in current at the ranges of magnet currents used in this plant, i.e., 4,000 and 7,500 amp. Two such instruments were built, one using an electronic device and the other a redesigned Leeds & Northrup Micromax.

Figure 21.1 is a simplified schematic diagram for an electronic suppressed-zero ammeter designed to indicate and record currents lying in the range of from 7,000 to 8,000 amp. The current was indicated by a standard panel meter and was recorded by an Esterline-Angus recording meter. Both meters had uniform scale divisions running from 7,000 amp at the left end to 8,000 amp at the right end of the scale. Each division of the scale corresponded to a 20-amp increment in current; the load current was therefore indicated and recorded directly to the nearest 10 amp.

To avoid the difficulty of building a sufficiently stable d-c amplifier, the d-c signal was converted to an a-c signal and fed to a stable a-c amplifier.

The current to be measured passed through a 10,000-amp 50-mv shunt. This current may be considered as the sum of two currents: 7,000 amp plus the current above 7,000 amp. The shunt voltage developed by the first 7,000 amp was balanced by a reference voltage. When the dry cell supplied 1 ma to the resistor in one of the leads from the current shunt, the voltage developed across this resistor was equal to the shunt voltage corresponding to a 7,000-amp load current. Therefore the voltage signal seen by the converter and transformer was zero when the load current was 7,000 amp.

As the load current increased from 7,000 to 8,000 amp, the voltage signal that reached the converter and transformer would increase linearly. The shunt voltage developed by current in excess of 7,000 amp was changed by the converter and transformer to a square-wave 60-cycle voltage, was amplified by the two-stage a-c amplifier, and was then rectified by the rectifier tube in the half-wave voltage-doubler circuit. The d-c signal from the rectifier controlled the cur-

rent through the output tube. The current was indicated and recorded by the 5-ma meters in the cathode circuit. The indication of the meters was proportional to the number of amperes by which the load current exceeded 7,000 amp. The scales of the meters were therefore marked directly in load amperes, with 7,000 amp at the left-hand end of the scale.

This instrument can easily be modified to indicate and record magnet currents over any other 1,000-amp band lying between 0 and 10,000 amp, such as 4,000 to 5,000 amp, which is the load-current range for Beta magnets. Since the current shunts on all magnets were rated 50 mv, 10,000 amp, the 5-mv full-scale deflection of the electronic ammeter was made to correspond to any 1,000-amp range simply by adjusting the reference voltage. Of course, the scale expansion varied with the amount of zero suppression.

This meter was used to indicate magnet currents in one magnet for about two months. In general the test was very satisfactory, but owing to the effects of temperature changes on the reference voltage, the instrument gave a false indication of load-current drift of about 20 amp during a 24-hr period. Allowing for the 20-amp false indication, this meter still indicated currents much more closely than a regular switchboard meter.

At the same time the electronic meter was being tested, a test was made on a suppressed-zero ammeter made from a redesigned recording Leeds & Northrup continuous balancing potentiometer, commonly called a Micromax. (A detailed description of the Micromax recorder appears in Part II.) A standard 5-mv model S Micromax was changed so that the first 35 mv of the voltage across the load-current shunt was balanced. Thus the slider remained at the left-hand side of the scale until the load current increased to 7,000 amp, 35 mv across the shunt. Then, as load currents in excess of 7,000 amp generated shunt voltages larger than 35 mv, the slider moved along the potentiometer slide-wire until the voltage across the shunt due to currents in excess of 7,000 amp were balanced by the voltage from the left-hand side of the potentiometer to the slider.

The scale was graduated uniformly starting at 7,000 amp at the left-hand end and running to 8,000 amp at the right-hand end of the scale. Each scale division corresponded to a 10-amp increment in current; the load current was indicated and recorded to 5 amp instead of 10 amp as in the electronic meter.

The Micromax mechanical system had sufficient backlash to cause as much as a 5-amp error in the current indication. That is, if the current had increased to a higher level and then had fallen off less than 5 amp, the meter would not indicate a current change owing to

the backlash of the mechanical system. This instrument did not respond to current changes as rapidly as the electronic meter and was not dependable for indicating rapid changes in load current. It was a very reliable instrument for slow changes that might occur over a period of minutes.

The general feeling was that either instrument indicated load currents accurately enough for proper operation. The choice of instrument depended on a few of the advantages or disadvantages of the instrument under consideration. The electronic meter not only indicated absolute current fairly closely but also responded to rapid current changes. The Micromax indicated absolute current very accurately but did not respond to rapid current changes. The reference voltage in the Micromax was automatically checked against a standard cell every 45 min. To check the reference voltage of the electronic meter against a standard cell, it was necessary to close a switch and adjust a potentiometer in the reference circuit until a balance indication was observed on the output meter. The standard cell and switching arrangement have been omitted from the simplified schematic diagram of Fig. 21.1. The drift in dry-cell voltage was small; therefore for most applications a check on the reference voltage once a week was adequate.

Almost all the wiring and components of the electronic instrument operated at or near ground potential, and the electrical circuit in the Micromax instrument operated at the potential of the current shunt above ground. The current shunt in the plant operated as much as 600 volts above ground. The complete instrument used in this test had to operate at shunt potential because sufficient insulation was not built into the instrument at the factory. Although this instrument was designed to operate only at a low potential to ground, similar instruments were available with sufficient insulation for this application.

Even though a Micromax was available with the electrical system adequately insulated from ground, operation at shunt potential was very objectionable because the electrical system had to be isolated from the current shunt before any adjustments or maintenance could be performed on the instrument. Because of the danger of accidentally causing a ground fault by grounding the magnet electrical system, any instrument that had to be periodically connected or disconnected from the magnet electrical system was considered undesirable. Neither type of suppressed-zero ammeter was installed permanently in the CEW-TEC plant.

A detailed schematic drawing of the electronic suppressed-zero ammeter used in the test is shown in Fig. 21.2. A detailed schematic drawing of the Micromax has not been included because the circuit is

the same as the circuit for a commercial instrument except for the one change indicated earlier, namely, the self-balancing potentiometer does not function until the shunt voltage becomes larger than the reference voltage. The reference voltage is the drop across a fixed resistor connected in series with the slide-wire of the self-balancing potentiometer.

Magnet-current variations occurring in less than a few minutes were of much more concern than variations occurring over periods of hours. Under routine plant procedure the accelerating voltage on each channel was adjusted by the operators approximately once every 15 min. A drift in magnet current over a period longer than 15 min was therefore compensated for by voltage adjustments on individual channels. Changes lasting just a few minutes went unnoticed for the most part. Changes that occurred in a still shorter period of time, a minute or less, could not be compensated for by the operator. Hence close regulation of magnet current was a requirement that in turn dictated a need for an instrument stable and sensitive enough to detect a change of 1 part in 5,000 in magnet current occurring in a fraction of a second.

An instrument was designed which was sufficiently sensitive to indicate these small changes. This device was essentially a suppressed-zero ammeter. A reference-voltage signal was constantly compared with the voltage drop across the current shunt. The voltage difference in these signals was amplified by a high-gain d-c amplifier and then measured by a recording voltmeter. Current variations from the predetermined value were recorded by the recording meter, in which each scale division corresponded to 1 amp. Thus, for magnet currents of 7,500 amp, current variations of less than 1 part in 7,500 were recorded.

Reference to the simplified schematic drawing, Fig. 21.3, points out that a very high-gain d-c amplifier is obtained through the use of a very sensitive galvanometer if the ratio of the total plate resistance to that portion of the plate resistance in the galvanometer circuit is large, 480,000 to 1 in this device. As the galvanometer rotates owing to an increase or decrease in voltage drop across the current shunt, the quantity of light reflected onto the photocell by the galvanometer mirror will change until the grid voltage is such that the drop across the portion of the plate resistor in the galvanometer circuit changes the same amount as the shunt voltage changed. Then the galvanometer circuit will be balanced, and the galvanometer will cease to rotate. Thus, since the voltage across the portion of the plate resistor in the galvanometer circuit is proportional to the total voltage drop across the plate resistor, the voltage change measured by the output meter is proportional to the current change through the shunt.

When a sensitive d-c instrument of this type is constructed, particular attention must be given all the connections in the galvanometer circuit where the d-c voltage signal to be amplified is very small. Current variations of 1 amp correspond to 1 scale division and give only 5 μv across the 10,000-amp 50-mv magnet-current shunts. Thermally induced voltages that are large compared to 5 μv can be generated at the various connections in the galvanometer circuit. In order to keep thermal voltages to a minimum, the instrument had copper-to-copper contacts at all the critical circuit connections. To reduce thermally induced voltages further, the galvanometer or reference circuit was enclosed in a cabinet so that the connections would not be subjected to sudden temperature changes.

The electrical circuit of this instrument operated at the potential of the current shunt above ground. The objections to the Micromax suppressed-zero ammeter operating at the potential of the current shunt also apply to this instrument.

The galvanometer was made by the General Electric Company. The galvanometer, light source, photocell, and amplifier tube were assembled as a unit that is commerically known as a fluxmeter. The fluxmeter would not respond to extremely fast changes, and the use of this instrument was limited to monitoring current changes lasting at least 5 sec.

The fluxmeter was sensitive to vibration and had to be mounted on a floating chassis suspended by springs or supported by sponge rubber. Although this was a disadvantage, it was possible with sufficient care to mount the fluxmeter so that the effects of vibration were small enough to be neglected.

A test instrument was assembled following the circuit principles shown in Fig. 21.3. Tests on the instrument proved satisfactory enough for parts to be ordered for a similar instrument for each magnet. When the parts arrived about a year later, the necessity for such an instrument was questioned, and as a result the instruments were never assembled.

A detailed schematic diagram of the fluxmeter current recorder is shown in Fig. 21.4.

The amplifier of the CEW-TEC amplidyne stand-by regulator described in Chap. 3, Sec. 5.2, makes an excellent magnet-current monitor. The amplifier is similar, except that it has much larger gain, to the amplifier in the electronic suppressed-zero ammeter. An output meter on the regulator amplifier monitors the magnet current continuously and will respond to very rapid changes in magnet current because the amplifier was designed to have a minimum time delay. Each scale division of the output meter corresponds to a 0.5-amp

current change through the shunt, thus permitting current changes of 0.25 amp to be detected.

Although the meter itself is sensitive to 0.25-amp current changes, the voltage feed-back circuit used with the current regulator limits the actual use of the meter to current variations of 0.5 amp. Magnet currents of 4,000 amp can be monitored therefore to 1 part in 8,000. Thus, if current regulation to 1 part in 5,000 is considered adequate, this instrument indicates current variations that are so small they are assumed not to affect production. A recording meter may be connected in series with the indicating panel meter.

The amplidyne regulator was installed on the last CEW-TEC plant magnet to go into operation. Operation of this installation showed the stand-by regulator to be superior to any other current monitor or recorder used in this plant. Most of the electrical circuit operated at or near ground potential. Thus test or general service work could be performed on most of the instruments with minimum danger to personnel and without fear of grounding the magnet electrical system.

The need for accurate current recorders was somewhat reduced by meters that indicated the total production of all the channels using the same magnet. When there was a reduction in production which could not be attributed to other operating conditions of the system at that time, it was generally assumed to be due to inadequate regulation of the magnetic field, since the field was the only element common to a number of process channels. Failure of any one channel could affect total production by only a few per cent, while a change in magnetic-field intensity of but 1 part in 2,000 would definitely be accompanied by a change in production. Not every meter change meant magnetic-field change, nor would the meter indicate if current regulation had gradually become worse or if the regulation had been poor for several hours. The effectiveness of this indication depended on comparing production over short periods of time.

2. ALARM FOR LOSS OF CURRENT REGULATION

Alarm circuits have been suggested for indicating the loss of magnet-current regulation. As indicated earlier, optimum plant production is lost if magnet current is not regulated very accurately.

For an alarm circuit to be of value it must distinguish between normal minor variations and more extreme variations which may result in unsatisfactory operation. The alarm may be used to ring a bell, turn on a signal light, or even change regulators automatically. A spare regulator was kept in continuous stand-by service so that regulators could be changed at any time. Past experience had shown that the regulator was usually the cause of poor current regulation.

Most alarm systems used stability of the exciter voltage for the main generator field as an indication of the magnet-current regulation. In a current-regulating circuit of the type used in the CEW-TEC plant, a small change in magnet current caused a rapid corrective change of several volts in the exciter voltage.

One alarm consisted essentially of a contact-making voltmeter. The meter contacts were adjusted to close and actuate the alarm circuit when the exciter voltage increased or decreased 20 volts out of a normal operating voltage of 140 volts. Each time the operating current, and consequently the exciter voltage, was changed, the meter had to be reset. In production practice, magnet current was seldom changed, and consequently the resetting was no great inconvenience in the use of the absolute-voltage alarm.

The contact-making voltmeter alarm was used on several of the magnet installations. It was usually referred to as an "exciter alarm" because it was tripped by a given change in exciter voltage. This particular type was used to ring a bell but was not used for automatic transfer from one regulator to another.

Another type of alarm was used to transfer regulators as well as to ring a bell when the exciter voltage changed by a certain amount. This type did not require resetting each time the operating current was changed. In Fig. 21.5 it will be observed that the alarm was composed of a coupling circuit through which a relatively fast exciter-voltage change would reach the grids of the tubes. If the exciter voltage increased, one tube would conduct, and, conversely, if the voltage decreased, the other tube would conduct. The conducting tube operated the relay in the common plate circuit. The relay in the plate circuit energized another relay, which closed a sealed-in contact and also closed the alarm circuit.

Isolating condensers permitted the entire alarm circuit to operate at ground or at a d-c potential completely independently of the exciter voltage. This was a very desirable feature for the General Electric current regulator because, when the exciter circuit was grounded, external disturbances reached the regulator and thus tended to cause poor current regulation.

The alarm has not been tested on a plant magnet for an extended period of time as an automatic-transfer device for the current regulators. Parts were purchased for building such a device, and it was intended that the alarm with automatic-transfer feature be installed when the magnets were shut down for routine servicing. A detailed schematic drawing of the automatic-transfer device to be installed in the plant is shown in Fig. 21.6. The original regulators installed in the plant were not designed to be used with an automatic-transfer device.

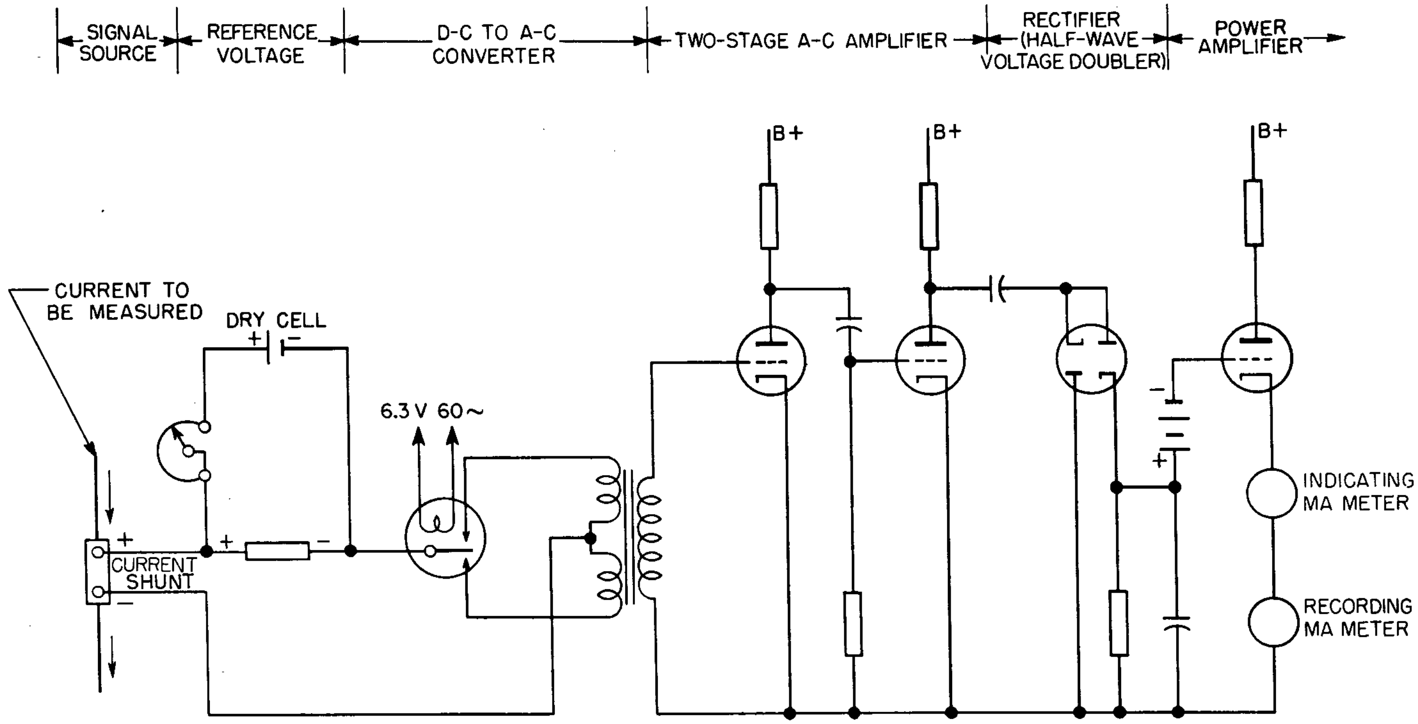


Fig. 21.1—Simplified schematic diagram of an electronic suppressed-zero ammeter. (See Fig. 21.2 for complete schematic diagram.)

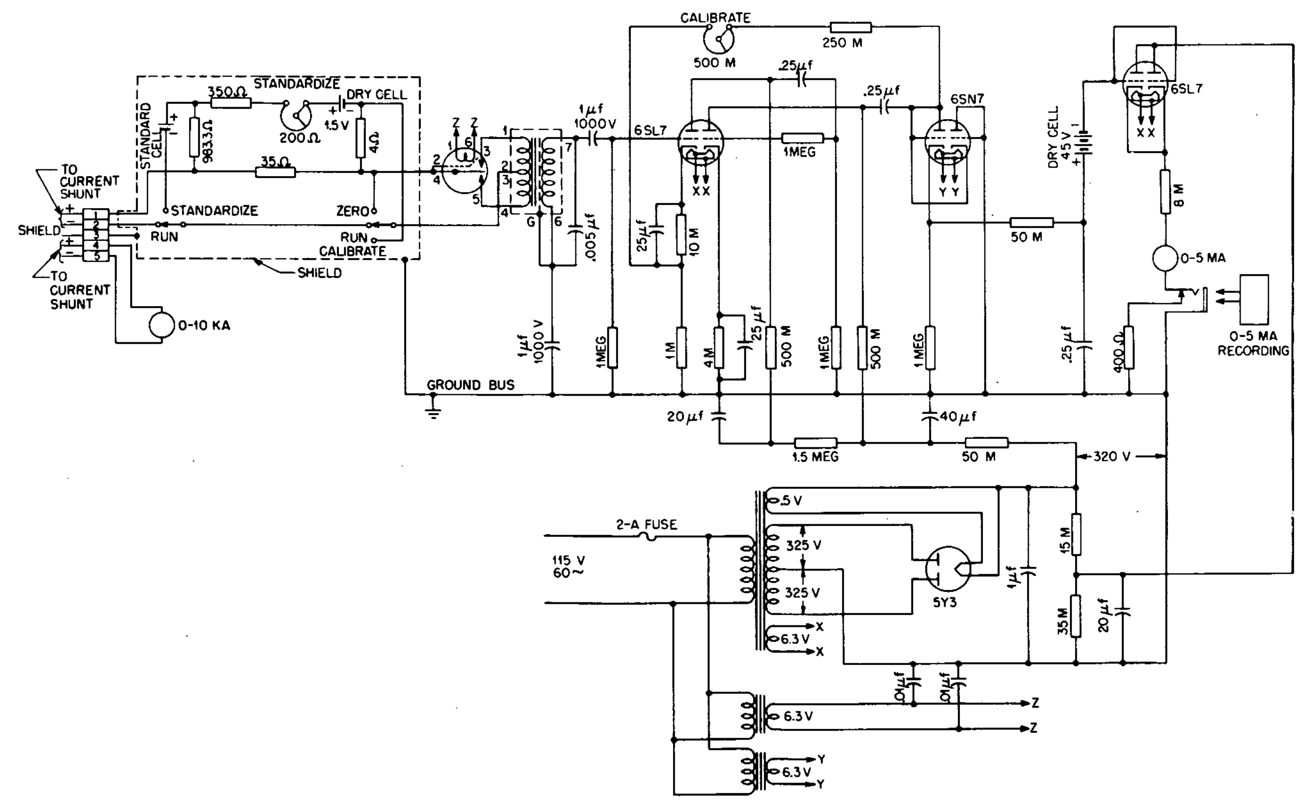


Fig. 21.2—Schematic diagram of an electronic suppressed-zero ammeter.

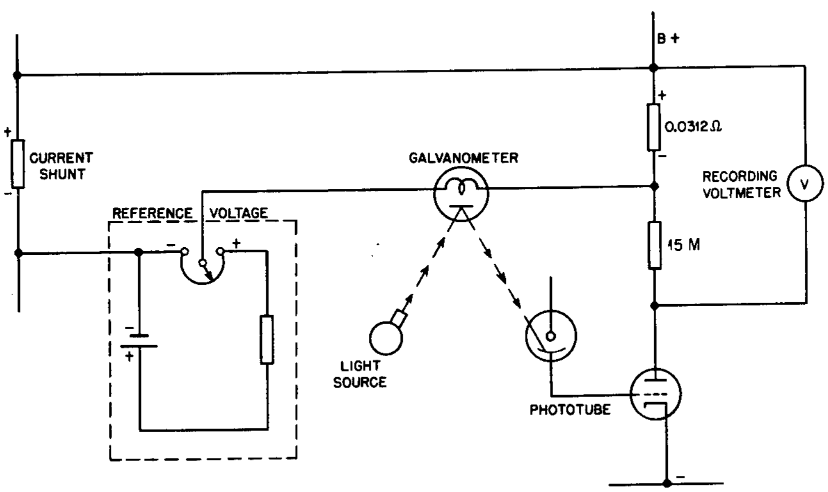


Fig. 21.3—Schematic diagram of the fluxmeter type of current recorder. (See Fig. 21.4 for detailed schematic diagram.)

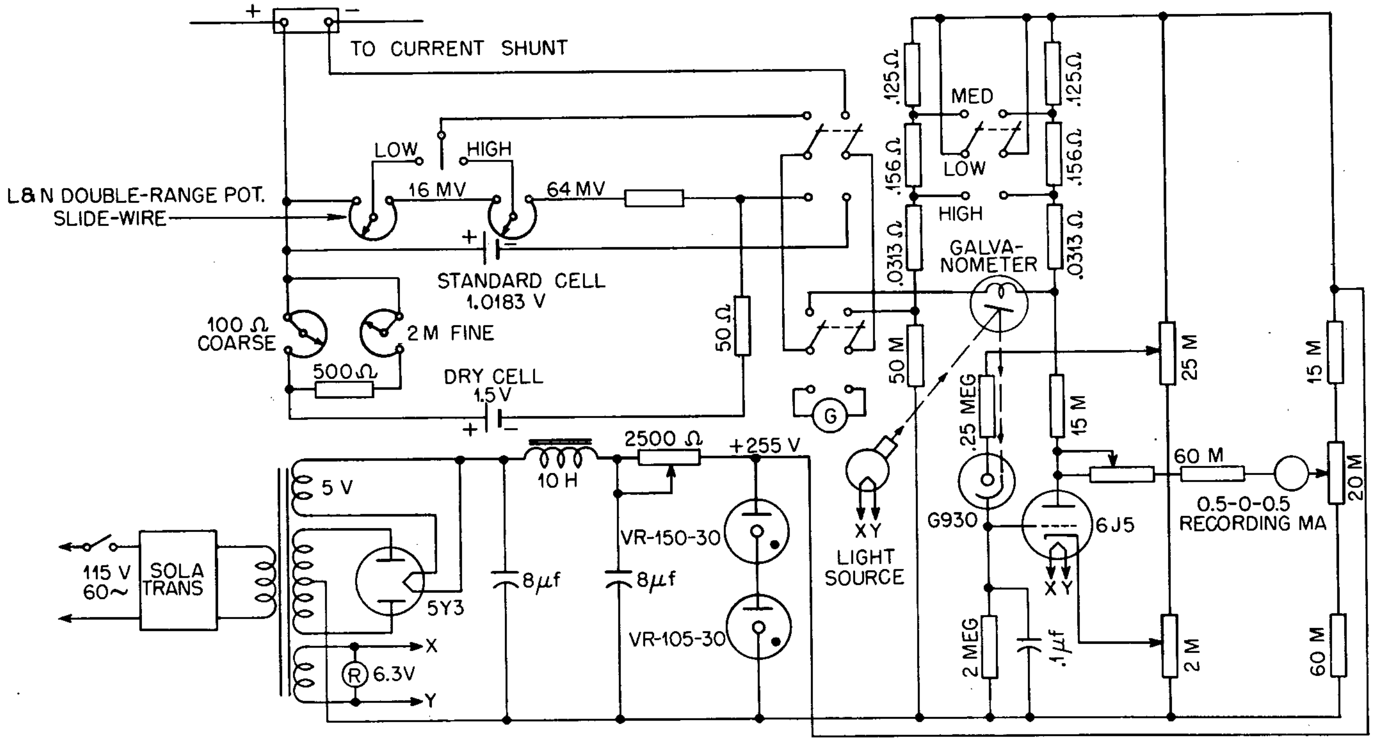


Fig. 21.4—Schematic diagram of the fluxmeter type of current recorder.

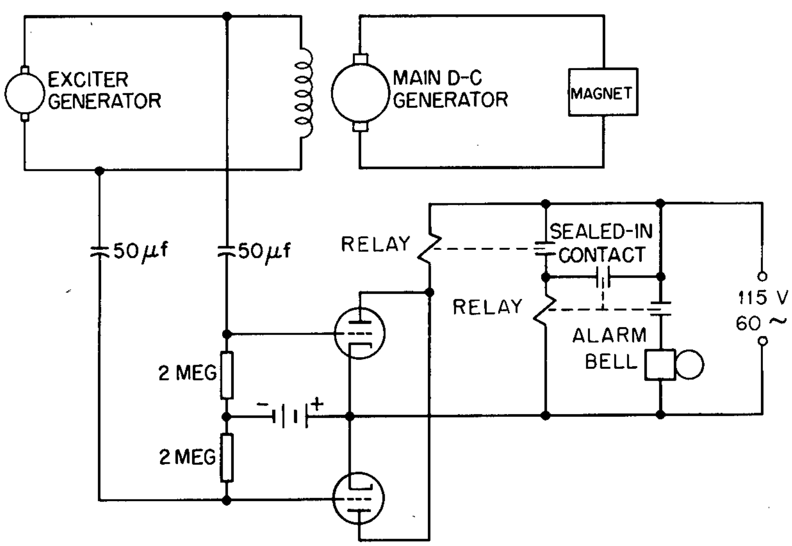


Fig. 21.5—Schematic diagram of the electronic-exciter alarm system.

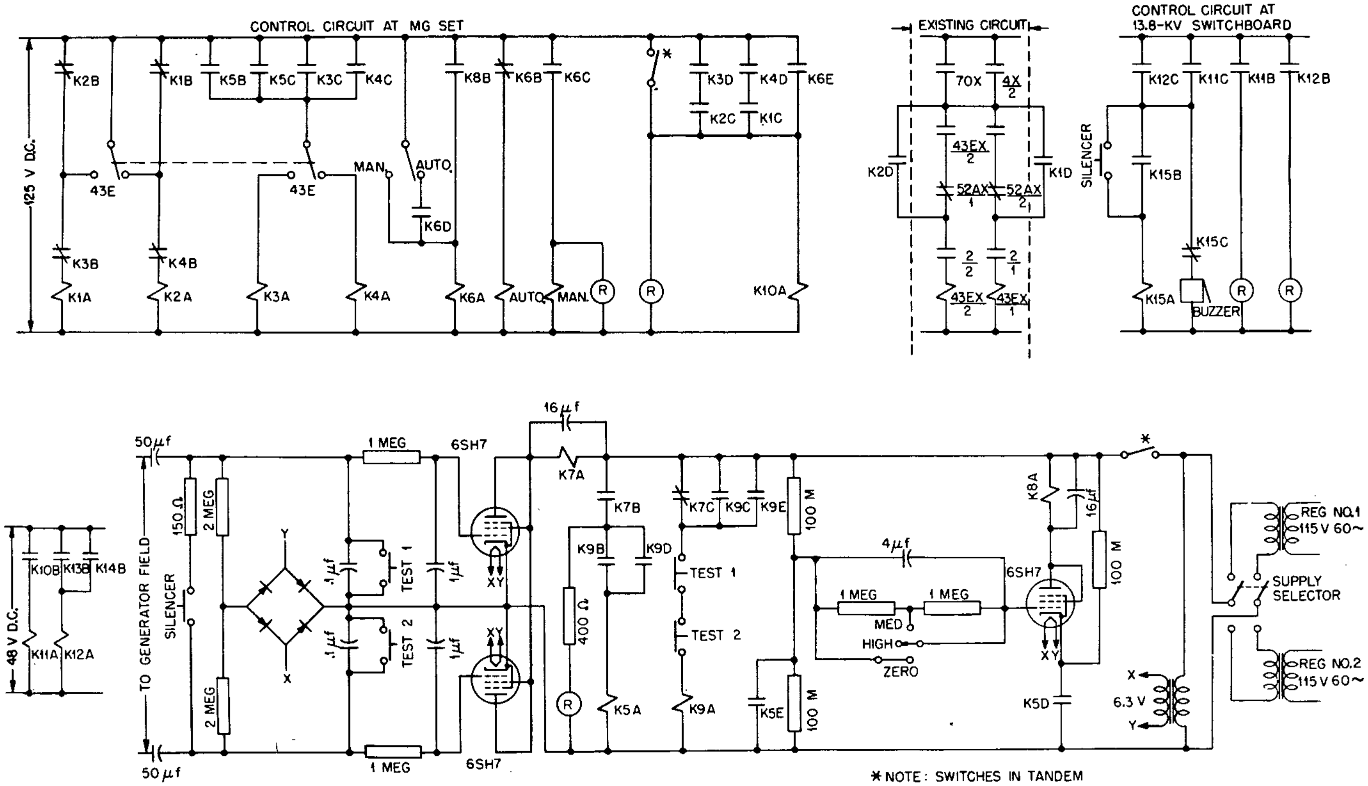


Fig. 21.6—Schematic diagram and control circuit of the electronic-exciter alarm including regulator transfer.

Chapter 22

CURRENT REGULATORS

Magnet-current regulators used with the electromagnetic process at CEW-TEC were very similar to the regulators used on the prototype magnets at the Radiation Laboratory at Berkeley, Calif. Plant operation has shown that plant magnet current should be regulated to at least 1 part in 5,000. The regulators for the plant magnets were furnished by the General Electric Company. The regulator used a galvanometer photocell arrangement similar to that of the early magnet regulators used by the Radiation Laboratory.

An amplidyne regulator developed at CEW-TEC as a probable replacement for the galvanometer regulators is similar to the converter regulator developed at the Radiation Laboratory, the main difference being the addition of the amplidyne generator as the power amplifier to replace the conventional machines that require much larger quantities of control power and have a much slower speed of response.

The plant record of the General Electric regulators is given in some detail because this regulator was installed on all but one of the plant magnets. The main aspects of the development work on regulators and in particular on the converter regulators, of which the amplidyne regulator is one example, have been included in the volumes of the National Nuclear Energy Series prepared by the Radiation Laboratory at Berkeley, Calif. This volume will therefore include only such references to the amplidyne regulator as are necessary to give a complete picture of magnet-current regulators used in the CEW-TEC plant.

1. GENERAL ELECTRIC REGULATOR

A block diagram of the magnet electrical system using the General Electric regulator is given in Fig. 22.1. In addition to the main current feed-back loop four other feed-back loops were employed. A complete schematic diagram is shown in Fig. 22.2.

Magnet currents flowed through a 10,000-amp 50-mv shunt. The millivolt signal from the current shunt was supplied to a zero-torque galvanometer, where it was balanced against a reference voltage. The reference voltage was generated across a resistor by plate current from a triode. The voltage across the plate resistor was balanced against a standard cell through a zero-torque galvanometer photocell arrangement. This provided a reference voltage, very nearly as constant as the standard cell, from which reasonable quantities of current were available.

Another compensated or zero-torque galvanometer balanced the shunt voltage and reference voltage. The corrective effect of the galvanometer was initiated through a photocell, as in the balancing of standard cell and reference voltages. To maintain balance between reference and shunt voltages the photocell signal had to go through the control loop, consisting of amplifier, exciter, generator, and shunt.

If the regulator system in Fig. 22.1 is assumed to be free from all feed-back loops except the main current feed-back loop, a signal due to an unbalance between the reference voltage and the shunt voltage will affect the system as follows:

If the magnet current and hence the shunt voltage is too small, the signal will be of such polarity as to increase the magnet current. The small signal of a few microvolts will be amplified by the d-c amplifier and supplied to the grid control of the thyratron rectifier. The rectifier in turn will control the field current to the exciter by acting as a variable resistor in the field circuit. The exciter will supply current to the field of the main generator and thus control the generator output voltage. Magnet current and thus shunt drop will be controlled by the output voltage of the main generator. The shunt potential will remain very nearly equal to the reference voltage except during transient disturbances. Following a disturbance the magnet current will go through a damped oscillation before settling down to the normal operating value.

To keep the system from oscillating, the galvanometer had to have a large time constant, which was obtained by feeding a signal back from the photocell amplifier. The current measuring circuit was unable to respond to rapid current changes. To make the system sensitive to rapid generator voltage changes, a signal was fed directly from the generator armature to the rectifier grid control. This feedback tended to hold the generator voltage constant over short periods but did not affect long-period equilibrium conditions.

In a normal regulator it should not have been necessary to use any other feed-back loops, but after the system was given a plant trial, two more feed-back paths were added. Through one of these, rapid

changes in generator voltage are fed to the galvanometer circuit. The effect of this signal is to speed up the galvanometer, which has just been slowed down by the feedback from the amplifier. Similarly, rapid changes in exciter voltage are fed to the galvanometer circuit.

The whole picture of how one feed-back loop acts in the presence of another feed-back loop is very complex, making it very impractical to calculate the regulator response. Cut-and-try procedure was followed in deciding on the feed-back loops and the constants for the components in these loops. Although the regulator has been used in the plant for about three years, it is not practical to predict how the regulator will operate under slightly different conditions.

The feed-back constants for the first two magnet electrical systems failed to give acceptable results on the third magnet electrical system in which slightly different generators were used. Instead of modifying the constants in the main generator voltage-to-galvanometer feed-back loop, the exciter-voltage feed-back loop was added. The cut-and-try procedure was followed until regulation was accepted as satisfactory.

Several changes in addition to the extra feed-back circuits were made in the general regulator design in an attempt to make the regulators more dependable as well as to improve normal current regulation. All the design changes were made after plant tests indicated a need for such changes.

Bulbs for the light sources in the reference voltage and in the regulator amplifier failed at an exceedingly high rate from the time the initial installation went into operation. In an attempt to reduce the number of lamp failures to a minimum, a 14-day replacement schedule was set up. Regulator failures due to burned-out lamps continued but at a lower rate. Tests indicated that the lamps were operating at temperatures above their rating and that sufficient light would be supplied at a much lower voltage and would result in a much lower temperature. In this application the lamps were enclosed in a lighttight metal case, lighttight except for the airtight section in which a lens focused the light onto the galvanometer mirror. Heat losses for a lamp enclosed in a metal case are very low compared to heat losses of a similar lamp exposed to air currents in an average room. The lamp voltage was reduced by inserting a 1-ohm resistor in series with the lamp filament. In the regulators that had a separate transformer for the light sources, a 250-ohm resistor was inserted in series with the primary winding of the filament transformer. Lamp failures were practically eliminated when the lamps were operating at reduced filament voltages.

All regulator installations in the main plant had a spare regulator that might be put into service at any time it was desired to remove the

operating regulator. In the initial installations the signal leads from the shunt were transferred from one regulator to another by a switch at the input to the regulators. There was no convenient way of checking the stand-by regulator before it was put into service, and as a result several regulator failures occurred when a faulty stand-by regulator was put into service. In order to check the operation of the stand-by regulator, the shunt signal leads were permanently connected to both regulators. Interaction between the stand-by and operating regulators, which was caused by the common shunt leads, disturbed the magnet-current regulation while the operation of the stand-by regulator was being checked. To overcome this difficulty separate shunt leads were supplied to each regulator which made it possible to check the stand-by regulator without interfering with the operating regulator.

The generator-voltage feed-back signal was originally supplied to both regulators through a common lead. As in the case of the shunt leads, interaction made it necessary to use separate leads to each regulator.

The zero-torque galvanometer (fluxmeter) gave considerable trouble and caused several regulator failures when the galvanometer coil stuck against the brass plate that limited the maximum rotation of the galvanometer armature. It had been found earlier at the Radiation Laboratory that galvanometer sticking could be prevented by mounting on the galvanometer coil a small tungsten pin that would strike a glass surface at the maximum rotation of the armature. This feature was added to the standard galvanometers used in the regulators, and the failures due to sticking galvanometer coils were immediately eliminated.

Since most regulator failures were due to the galvanometers and their light sources, the reference-voltage circuit was replaced by a dry cell. Dry cells have proved to be satisfactory voltage standards for magnet-current regulators. It was expected that nearly 50 per cent of the regulator failures would be eliminated by replacing the standard cell, galvanometer, light source, photocell, and triode by the dry cell. This improvement was not realized because in the plant installations the regulator cabinets were often subjected to very high temperatures. The cabinets were supposed to be temperature-regulated by a thermostat, but often the thermostat failed to operate, and the cabinet temperature would rise to very high values and remain there for days before an attempt was made to return it to a reasonable value. Tests have indicated that a dry cell may operate at normal room temperatures for months but will fail in a short time if the ambient temperature rises to 50 or 60°C.

After the thermostats and heaters were disconnected, the regulators operated at normal regulator-cabinet temperatures. Experience with

the two pilot-plant regulators and with the amplidyne regulator on one of the plant magnets in which Eveready 742 dry cells were used as reference voltage shows that the dry cells gave very good service when properly used. In fact the dry cell in the pilot-plant regulator gave a satisfactory reference voltage for two years and was still in service at the time of writing.

Dry cells (as used in these regulators, delivering 0.5 ma) drift about 0.3 per cent per month and have a temperature coefficient of about 0.02 per cent per degree centigrade. Although they have given good continuous service for two years, it is recommended that the dry cells be replaced once a year when continuity of service is of great importance.

The regulated power supply furnished with the regulators was found to drop out of regulation when the service supply voltage fell below 112 volts. The normal plant-supply voltage is 115 volts. The small margin between the normal supply voltage and the minimum voltage at which the power-supply regulator will operate was not adequate to allow for line-voltage fluctuations. In order to expand the lower range of usable line voltage, a 6Y6G tube was chosen to replace the 6L6G and a 5V4G rectifier was used to replace the 5U4G. The 6Y6G has a lower tube drop at zero bias than does the 6L6G. Also the 5V4G has a lower tube drop than the 5U4G. These tube changes expanded the minimum regulating voltage from 112 to 85 volts without altering the 130-volt maximum limit.

A complete service record of the galvanometer photocell regulators used on the plant magnets is not readily available. A six-month period from Jan. 1 to June 20, 1945, after a year of operation and experience with the regulators, was carefully reviewed, and it is this period on which the service record is based. The data were compiled from the logbooks of the 38 regulators installed in the plant. Nineteen of these regulators were kept in stand-by service while the other 19 were in operation. Only those regulators that failed to operate properly while they were connected in the current-regulating loop have been listed as regulator failures. The data for tube replacements and general service apply to all regulators.

Forty-eight regulator failures were listed during this six-month period. Poor regulation occurred 20 times, the load was lost 17 times, the load current rose to a maximum 8 times, and the regulator being placed into service failed to take control 3 times.

Most causes of poor regulation were not found. When the cause was discovered, however, it was usually found to be bad tubes. Other factors, such as a defective thermostat and loose connections in the regulator, have been credited with causing poor regulation.

The reference voltage decreases to zero when the reference lamp burns out. The current regulator will thus decrease the load current to zero in an attempt to keep the shunt and reference voltages equal. In most cases a loss in load current occurred because the reference lamp burned out. Broken galvanometer suspensions, general galvanometer trouble, and tube failures also caused the load current to be lost.

In most cases a rise of the load current to a maximum was caused by a burned-out lamp in the amplifier. Bad tubes and improperly adjusted fluxmeters also caused the current to rise to a maximum.

Before the tungsten and glass stops were mounted on the galvanometer, there were several instances where the stand-by regulator failed to take control when placed in operation. There were no failures due to sticking galvanometer coils during the six-month period under discussion. Of the three reported failures in which the stand-by regulator failed to take control, one was caused by a bad 6SH7 tube, one was due to improper bias on the 6J5 tube, and the cause of the third failure was not found. Automatic transfer of regulators could not be used until such failures were reduced to a minimum.

During this period all the regulators received the following total of lamp and tube replacements and dummy loadings: complete lamp replacements (two lamps), 456 times; complete tube replacements (11 tubes), 91 times; and dummy loadings, 950 times.

In addition to the scheduled maintenance, 152 instances of unscheduled maintenance were performed on the regulators. Unscheduled maintenance usually involved such maintenance as adjusting the fluxmeters, zeroing the fluxmeters, cleaning the optical system, adjusting 6J5 bias, replacing tubes (in addition to the scheduled replacements), and general maintenance.

If the figures for the six-month period just discussed are assumed to be average for the plant, then annually the regulators had approximately 100 failures, 1,000 scheduled lamp replacements (total of 2,000 lamps), 200 scheduled tube replacements (total of 2,200 tubes), and 2,000 dummy loadings. Also the regulators received over 300 instances of unscheduled maintenance.

2. AMPLIDYNE REGULATOR

The magnet-current regulator designed and built at CEW-TEC as a probable replacement for the galvanometer General Electric regulator used a voltage amplifier similar to the converter regulator built at the Radiation Laboratory. An amplidyne was used as the power amplifier, thus taking advantage of the low excitation power and high speed

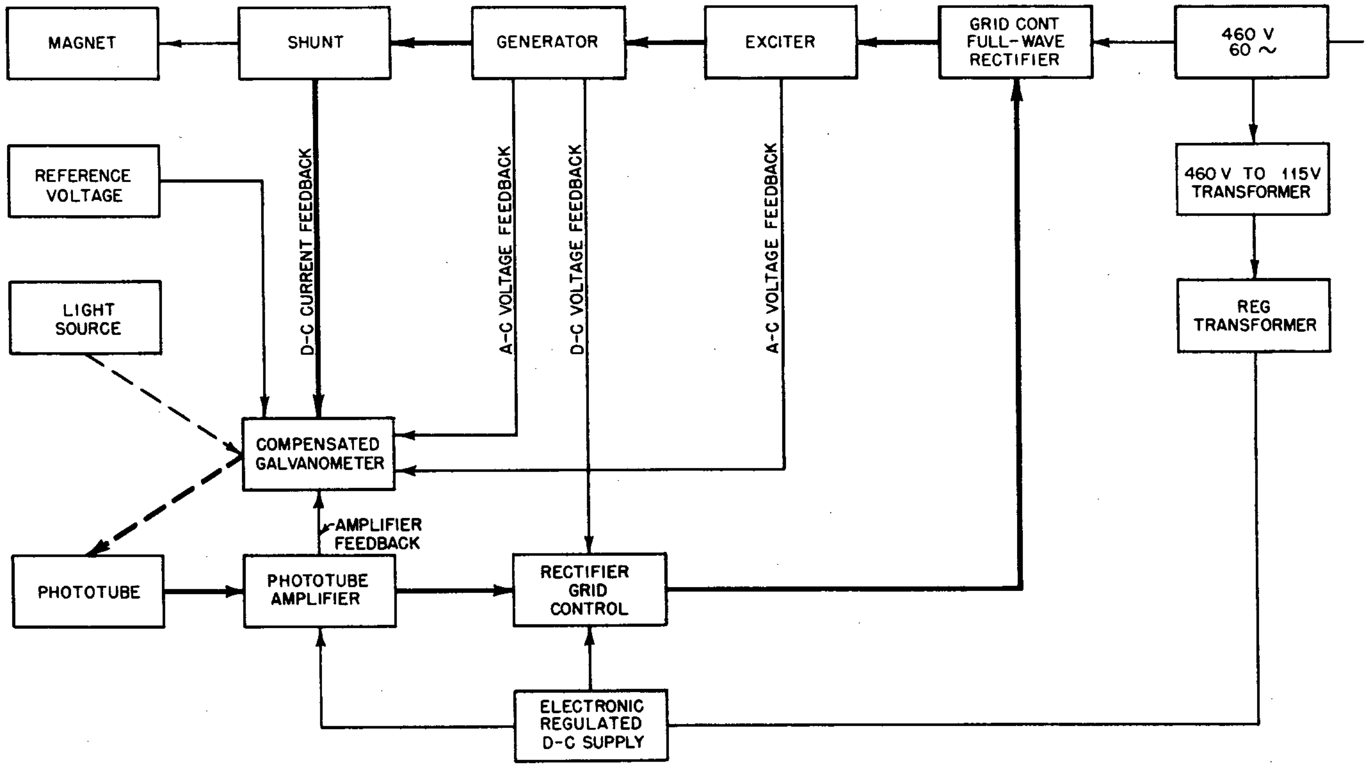


Fig. 22.1—Block diagram of the General Electric regulator system.

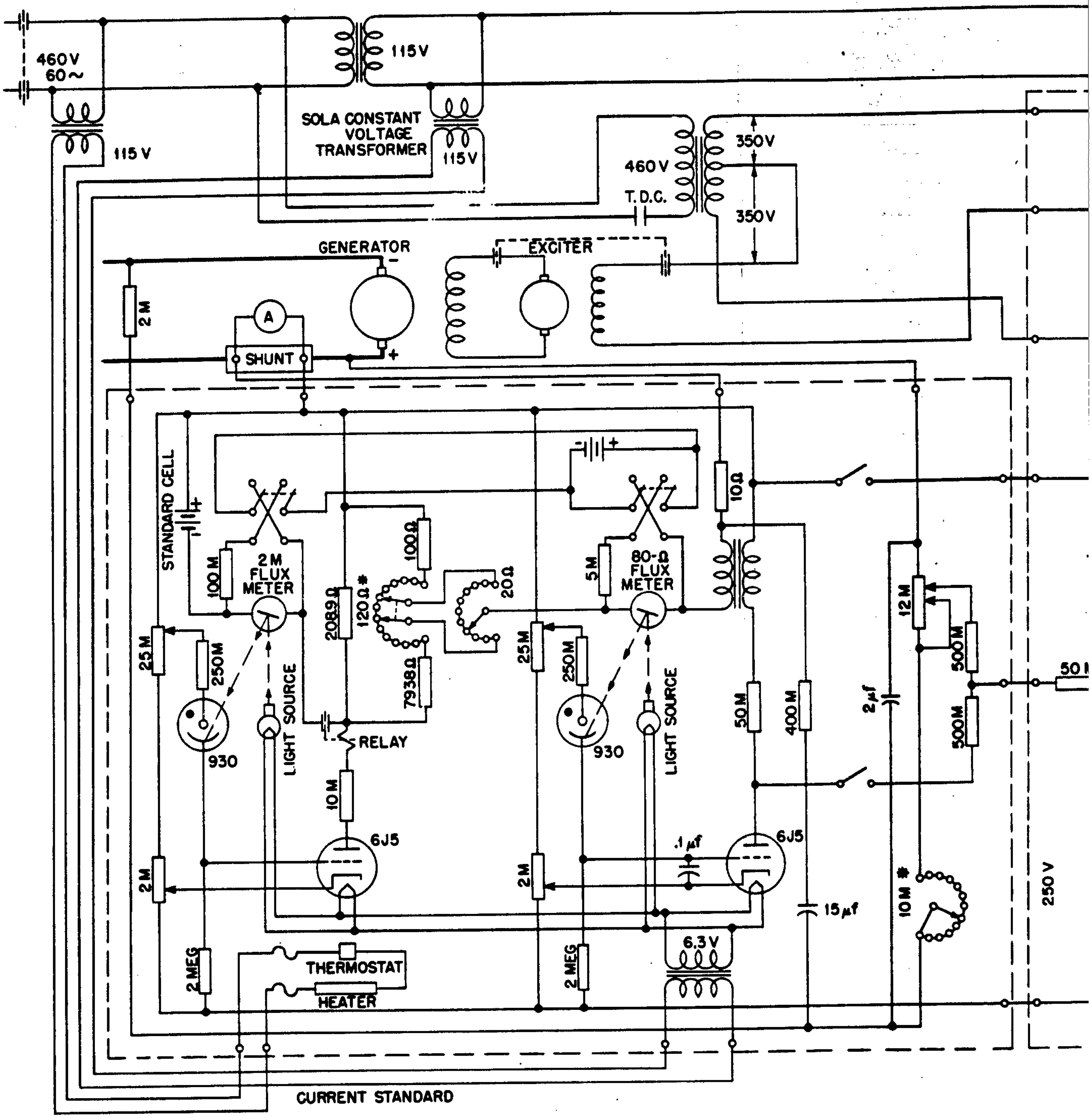


Fig. 22.2—Schematic diagram of the General Electri

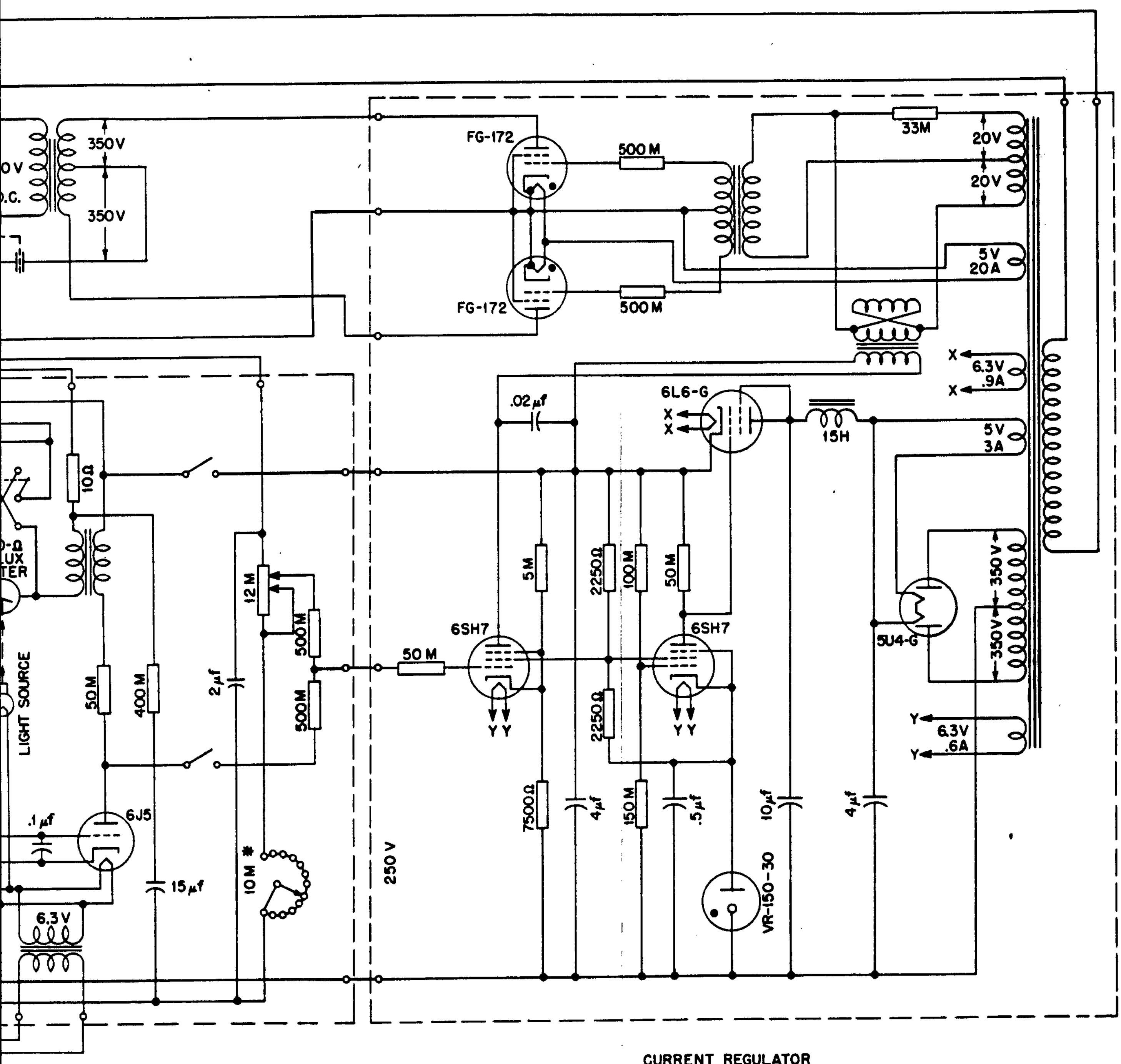


Fig. 22.2—Schematic diagram of the General Electric regulator.

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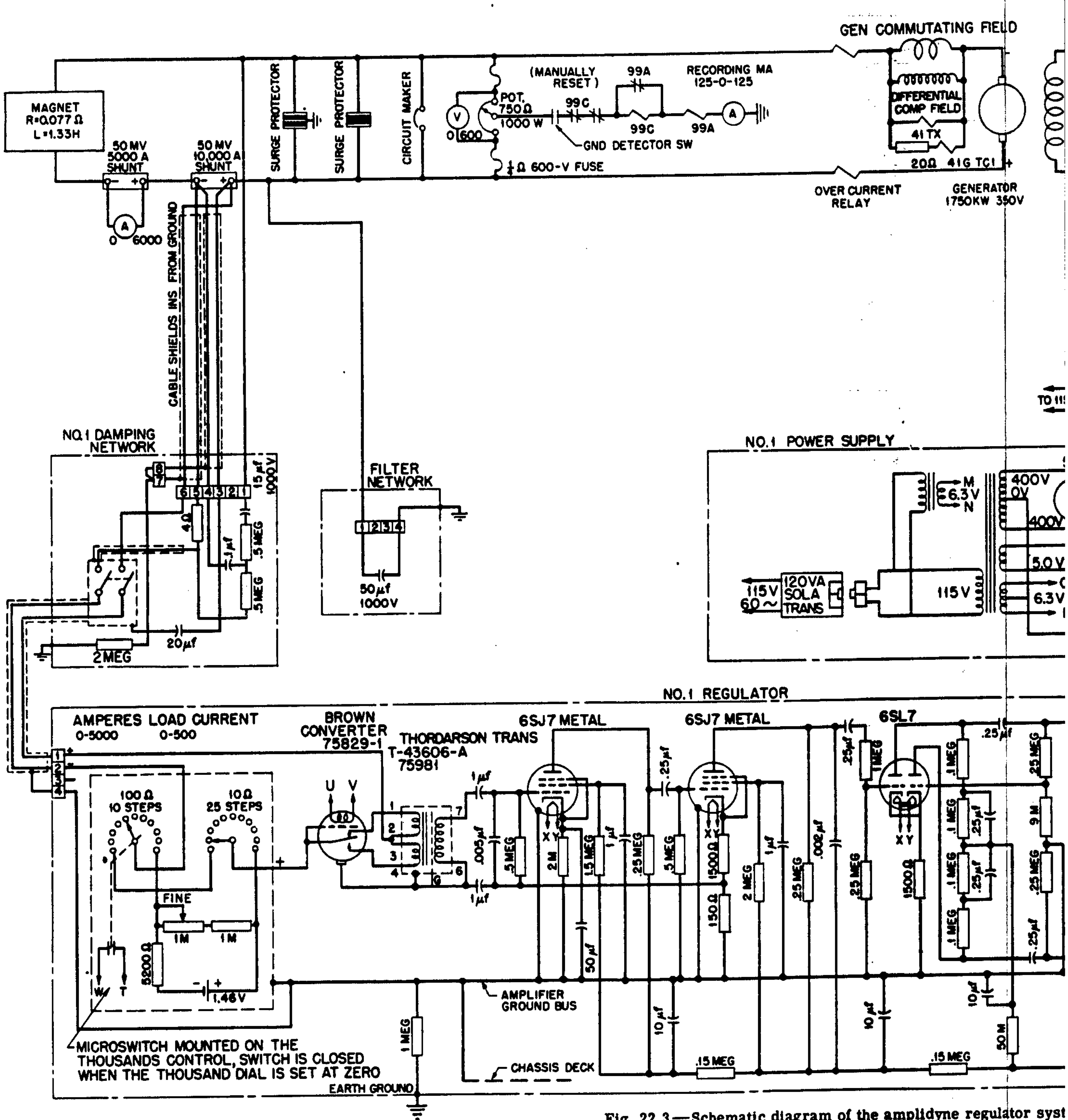
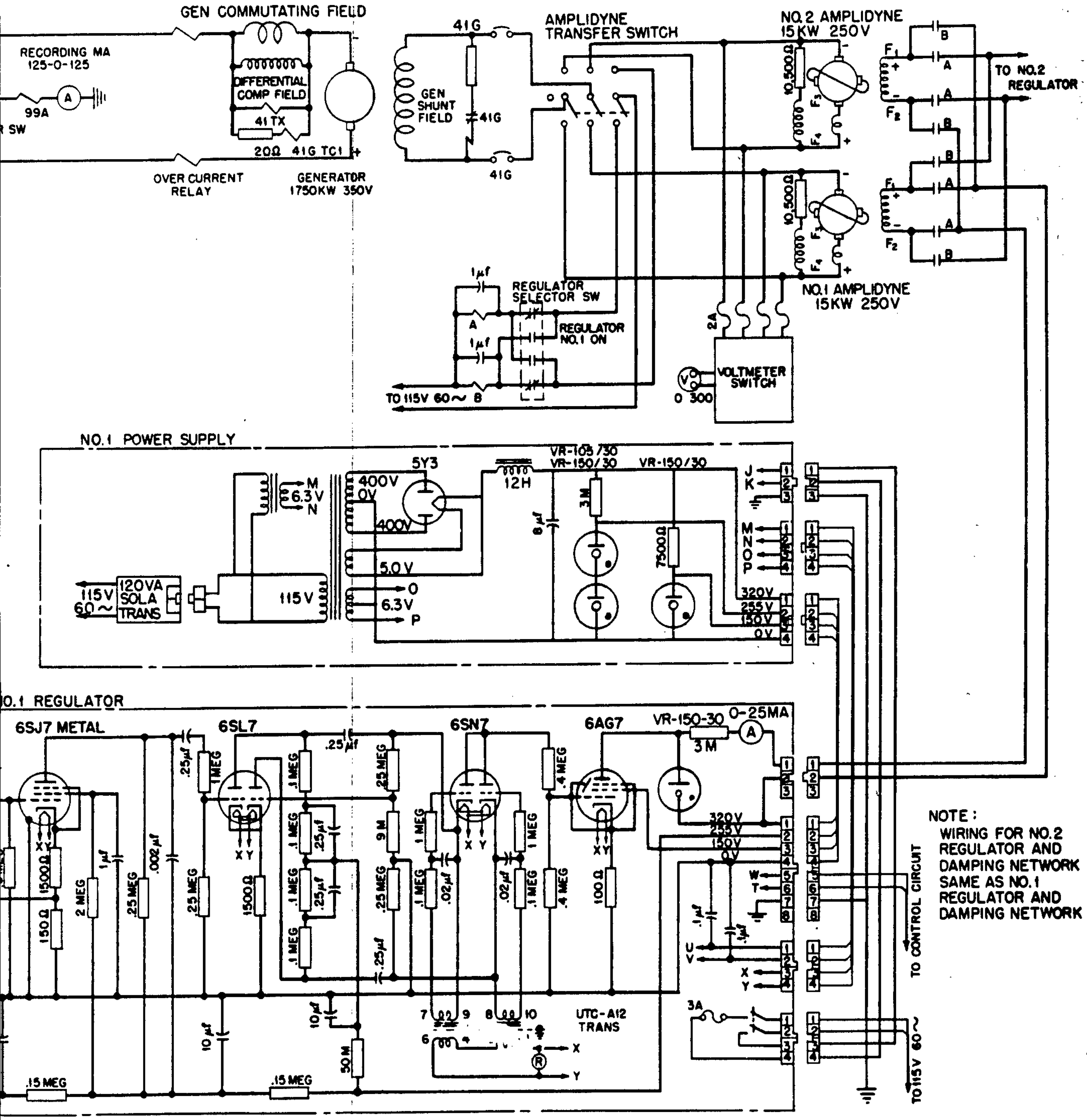


Fig. 22.3—Schematic diagram of the amplidyne regulator syst



—Schematic diagram of the amplidyne regulator system.

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of response inherent in an amplidyne. A complete circuit diagram has been included (Fig. 22.3) so that the two types of regulator used in the plant may be readily compared.

The amplidyne regulator was first installed in the Beta pilot plant. The voltage amplifier operated almost continuously for two years and did not receive any service work except for replacement of a rectifier tube that failed after nine months. All the other tubes, the converter, the dry cell used as a reference voltage source, and all the other components were used two years.

The amplidyne regulator was used on one Beta track for nearly a year. During this period there was not a case of amplifier failure nor an instance reported where the regulator was not regulating the magnet current to the minimum desired accuracy of 1 part in 5,000.

A similar installation was made in the Alpha pilot plant.

In the refining plant, where continuity of service was extremely important, a routine tube-replacement and service schedule was established. The rectifier tube was replaced every three months, all other tubes every six months, and the dry cell every six months. There was not a converter failure in any of the regulator installations over a period of several years, and because of the long life expected for these units they were not included in the replacement schedule. To the time of writing, the service schedule merely amounted to dusting off the components in the amplifier every three months.

The amplidyne regulator with careful design adaptation to a particular magnet was capable of regulating magnet currents to 1 part in 10,000. The tube replacements and service work were reduced to a minimum. The system proved to be very dependable.

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AEC, Oak Ridge, Tenn.